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Combustion Melting Characterisation of Solid Fuel Obtained from Sewage Sludge

Dongju Kim ¹ , Dong-kyoo Park ¹, Yong-taek Lim ¹, Soo-nam Park ¹, Yeong-Su Park ^{1,*} and Kyunghyun Kim ²

¹ Plant Engineering Center, Institute for Advanced Engineering, Yongin 17180, Korea; kimdongju@iae.re.kr (D.K.); parkdk@iae.re.kr (D.-k.P.); ytlm@iae.re.kr (Y.-t.L.); trackerdog@iae.re.kr (S.-n.P.)

² Department of Research Institute, Jinenertech Co., Ltd., Cheongyang 33317, Korea; wilymaster7039@gmail.com

* Correspondence: yspark@iae.re.kr; Tel.: +031-330-7878

Abstract: Solid fuelization technology can increase the heating value of sewage sludge such that it can be utilised as a fossil fuel substitutes. Reducing landfilling of bottom and fly ash resulting from heavy metals contained in sewage sludge is challenging. Hence, combustion melting technology (CMT), which can discharge bottom ash in the form of slag, has been proposed herein as an alternative to the conventional incineration technology. However, further research is required to improve the flowability of slag. Applicability of CMT for the stable treatment of heavy metals in the ash generated during the energisation of sewage sludge solid fuel has been reviewed. The change in the degree of fluidity was identified via a laboratory-scale fluidity measurement experiment following changes in melting temperature, mixing ratio of sewage sludge and sawdust, and basicity. The pouring index (PI) of sewage sludge solid fuel (pellet) was maintained at a level of about 60% at a basicity index of 0.8. Based on the results, the slagging rates and volume reduction rates, exhaust gas analysis, and heavy metal elution characteristics under oxygen enrichment were derived from a 2 ton/day combustion melting pilot plant experiment; thereafter, the feasibility of combustion melting of sewage sludge solid fuel was determined.

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Keywords: sewage sludge; slagging; pouring index; fluidity; basicity

1. Introduction

1.1. Sewage Sludge Generation and Treatment Status

The amount of sewage sludge, a by-product of sewage treatment, is rapidly increasing worldwide owing to the increase in population; for example, China has recorded a 13% increase in sewage sludge over a six-year period since 2007. In South Korea, 11,219 tons of sewage sludge are produced daily, and this amount has rising since 2009, owing to an increase in population [1]. Sewage sludge incurs high treatment costs due to high moisture contents (73~84%) as well as the heavy metals contained in ash [2–4]. Furthermore, as shown in Figure 1, 50% of the sewage sludge treatment in South Korea is handled under external consignment and metropolitan area treatments as of 2018, and fuelization technology accounts for 22% of total treatment [1].

Sewage sludge contains many organic substances, including microbial carcasses; therefore, it has high potential for use as fuel upon proper treatment. Generally, sewage sludge has an 80% moisture content before drying. The high heating value (HHV, dry basis) of sewage sludge solid fuel is approximately 85% (14.7 MJ/kg), while that of wood pellets is slightly higher (16.7 MJ/kg) [2]. The sewage sludge generated in South Korea, as of 2018, amounts to 11,219 ton/day, from which the solid fuel produced is estimated to be 2493 ton/day, which is equivalent to 31,313 GJ/day based on the HHV. According to the status of sewage sludge fuelization in South Korea, the annual growth rate is approximately 10%, from 2100 ton/day in 2016 to 2500 ton/day in 2018. As of 2018, the combined power

generation by co-combustion of sewage sludge fuel is 405 GWh, or 0.175% of the coal-fired power generation [5,6].

Figure 1. Sewage sludge treatment status in South Korea in 2018 [1].

Under the London Convention, marine pollution, caused by dumping of waste, has been prohibited. This, in conjunction with the enactment of the Act on the Promotion of The Development, Use and Diffusion of New and Renewable Energy, indicate that the demand for sewage sludge fuelization technology is expected to continually increase in the future.

1.2. Energisation by Fuelization

Various studies on the energisation of sewage sludge have been conducted in numerous countries. After pre-treatment, sewage sludge can be converted to solid fuel, biogas, biochar, bio-oil, and syngas through drying, anaerobic digestion, pyrolysis, and gasification technologies, or converted to heat or electric energy through direct combustion. The moisture content of sewage sludge is very high; therefore, direct combustion results in increased operating costs and reduced combustion efficiency owing to the use of auxiliary fuel [4,7]. Therefore, a solid fuelization process is required that involves the application of a drying technology for the removal of moisture through direct or indirect contact between sewage sludge and heat [4,7–10].

Sewage sludge solid fuelization technology can increase the HHV of sewage sludge as compared to that of fossil fuels, leading to the production of fuel that can be burned or co-combusted; the as-generated fuel can be used as a possible replacement of the conventional fossil fuels. This method can be used to produce solid fuel using only sewage sludge; however, in general, sawdust (a vegetable biomass) is mixed at 30–40% to the sewage sludge to avoid the formation of a glue-zone during the drying process. Additionally, sawdust acts as a binder in the pelletizing process, and increases the HHV of the solid fuel.

As discussed in Section 1.1., the use of sewage sludge fuel in South Korea has increased by 10% annually since 2016, and currently, four thermal power plants that co-combust sewage sludge solid fuel are in operation. In 2019, a B city thermal power plant in Korea co-combusted approximately 8000 tons of solid fuel, containing mixed sawdust and sewage sludge [11]. Unlike wood pellets, the treatment costs of sewage sludge can be covered by local governments, thereby reducing the unit cost of solid fuel production [7]. Therefore, the demand for thermal power plants is expected to increase, and the costs incurred will be relatively low.

However, owing to the presence of heavy metals in sewage sludge, large amounts of these metal contents in the fly and bottom ash generated during incineration have been reported [12]. Heavy metal content in the fly and bottom ash occurring during co-combustion with coal have also been reported to be problematic [13]. In addition, disposal costs have recently risen sharply due to limitations pertaining to the life spans of landfills, whereby additional locations for the treatment of incineration fly ash and bottom ash containing heavy metals need to be secured. For example, in the case of the landfill of incineration fly ash in South Korea, the treatment cost per ton has risen from \$213 to \$420. Hence, the combustion melting technology (CMT) of sewage sludge solid fuel has been proposed, which has the capacity to address pollution issues caused by heavy metals in ash, reduce ash weight, and allow for recycling to construction materials. However, the high cost of CMT operation with regard to sewage sludge has hindered the application of this technology. Nevertheless, a review of previous research on the melting of sewage sludge has revealed the aforementioned technology to be economic if the treatment cost per ton of sewage sludge is established at approximately \$400, making its application feasible.

1.3. Combustion Melting Technology (CMT)

CMT is considered an alternative solution to the problem of heavy metal discharge from conventional incineration methods. This technology involves pyrolysis, combustion, and melting processes. The synthetic gas generated by pyrolysis is burned in a combustion chamber, and the remaining solids are dissolved in a melting furnace to produce innocuous slag [14]. However, because high temperatures are required to melt the bottom ash, the energy consumption is high. In general, the melting temperature of sewage sludge ash was determined to be approximately 1200–1600 °C [8]. In addition, considering the need to use auxiliary burners for the smooth discharge of slag given the severe abrasion of refractories, research is required to improve the flowability of bottom ash [15]. In general, the melting temperature and flowability of ash are known to be affected by the basicity of the ash (CaO/SiO_2) [16].

As discussed in Section 1.2., in the case of solid fuelization of sewage sludge, 30–40% of sawdust is added to and mixed with the sewage sludge to avoid the formation of a glue-zone; thus, acting as a binder and increasing the HHV. Therefore, the effect of the amount of sawdust mixed on the melting temperature and flowability of sewage sludge solid fuel should be examined.

In addition, for combustion melting using auxiliary fuel, pure oxygen is generally used as an oxidant, and the melting temperature can be increased by lowering the heat loss; however, this increases the operating costs thereby lowering economic feasibility. Therefore, the effects on the melting of sewage sludge solid fuel and the emission of air pollutants under oxygen-enriched conditions should be examined.

1.4. Evaluation of Slag Flowability by Fluidity Measurement

The flowability of slag is closely related to the operating temperature of the furnace and the viscosity of the slag. An appropriate low level of viscosity is required for the smooth discharge of the slag in the melting furnace. Studies have demonstrated that a slag viscosity that ranges between 2.5 Pa/s and 25.0 Pa/s is appropriate for normal operation [17]. Therefore, measurement of the melting temperature and viscosity of the slag for the operation of the melting furnace is essential. However, these parameters are measured at high temperatures; this hinders their accurate measurements under laboratory conditions and makes the operation time-consuming and expensive. Owing to these challenges in the direct measurement of melting temperature and viscosity, indirect methods, such as prediction models and fluidity analysis, are sometimes used. In the case of coal, several melting temperature prediction models utilising the composition of ash have been developed and used, but no such prediction models have been developed for sewage sludge [18,19]. The development of such prediction models requires substantial analysis data on melting temperature. Another alternative is the fluidity analysis method,

which is relatively simple and easily reproducible; this has been proposed in various studies [8,11,16,19–23].

1.5. Objectives of the Study

This study seeks to examine the applicability of CMT to the stable treatment of heavy metals in the ash generated during the energisation process of sewage sludge solid fuel.

The purpose of this study is to specify the fluidity of the ash of the sewage sludge solid fuel and raw materials. In previous studies, there was a result that the change in basicity affects the melting temperature of the ash, and this study was conducted based on the hypothesis that there will be a change in fluidity according to the change in basicity. The research plan for this study is shown in Figure 2 below.

Figure 2. Schematic of the research plan.

Through laboratory-scale experiments, fluidity characteristics were analysed according to the mixing ratio of the sewage sludge and sawdust, melting temperature, and basicity of ash.

Thereafter, based on the laboratory-scale test results, we aimed to ascertain the applicability of the combustion melting of sewage sludge solid fuel under oxygen-enriched conditions using a 2 ton/day combustion melting pilot plant experiment.

2. Materials and Methods

2.1. Sample Preparation and Properties

Waste wood-based sawdust and sewage sludge were obtained from the sewage sludge solid fuel producer Jinenertech in South Korea for the experiment. The source of waste wood-based sawdust was a waste furniture and construction material processing company in Korea. Therefore, various types of wood were mixed, and also contained many impurities. The samples used in this study are shown in Figure 3.

To identify the physicochemical characteristics of the sewage sludge and sawdust, industrial analysis using the ASTM D 7582-15 test method was employed to measure moisture, combustible matter (volatile matter and fixed carbon), and ash [24]. Elemental analysis and calorific value assays were performed using the Quality Test and Analysis Method of Solid Refuse Fuel (2014) of the Republic of Korea to analyse the C, H, O, N, and S components and HHV [25]. In addition, EPA 3025 was used for heavy metal content analysis to determine the behaviour of these metals, and the Waste Processing Test Standard (2017) was applied to the heavy metal elution test [26,27].

Figure 3. Images of samples: (a) sewage sludge, (b) sawdust, (c) sewage sludge ash, (d) sawdust ash, and (e) sewage sludge solid fuel pellets.

To identify the thermal reaction characteristics of the target samples, the TGA-DTA (thermo-gravimetric Analysis–Differential Thermal Analysis) was conducted using the simultaneous thermal analysis–mass spectrometer (STA-MS, NETZSCH STA-409).

To measure fluidity, sawdust and sewage sludge were first heated and ashed in an electric furnace. The ashing was conducted as follows in accordance with the Quality Test and Analysis Method of Solid Refuse Fuel: 1. Samples were placed in an electric furnace and the temperature was raised to 250 °C at 5 °C/min, and maintained for 60 min, causing the evaporation of volatile matter; 2. the temperature of the electric furnace was raised to 550 °C for 60 min and was maintained at this temperature for 120 min to combust the sawdust and sludge sample; 3. if the sample was not completely combusted after one round, it was intensely heated again at 550 °C for complete combustion [28].

In addition, the sewage sludge solid fuel (pellet) input into the combustion melting pilot plant test under oxygen enrichment was produced at Jinenertech in South Korea by mixing sewage sludge and sawdust in a 68:32 ratios. This product is currently being supplied as a co-combustible fuel to D city and J city thermal power plants in South Korea.

2.2. Pouring Index (PI) Test

2.2.1. Experimental Method

The fluidity of ash was measured in accordance with the method presented by Kim et al. [16]. The size of the alumina boat used was 150 L × 15 W × 10 H, and the slope of the direction in which the sample was filled was maintained at 5°. To measure fluidity, the alumina boat was filled with the sample up to 20 mm (L_0) in the direction of the length, as shown in Figure 4. It was placed in the electric furnace, the temperature of which was raised by 10 °C/min to the target temperature, and maintained for 15 min. Then, the electric furnace power was turned off, temperature was cooled to below 1000 °C, the alumina boat was removed and cooled to atmospheric temperature, and the total length (L) of the cooled

sample was measured. The pouring index (PI) was calculated using the following formula, inputting the change in sample length before and after the experiment [16,20,29].

$$\text{PI (pouring index, \%)} = \frac{(L - L_0)}{L_0} \times 100 \quad (1)$$

where L_0 is the length of the initial sample, and L is the length of the slag that flowed down after melting. In this study, the same sample was measured four times to ensure the reliability of the data, and the average value of the measurements was used.

Figure 4. Schematic of pouring index experiment method [16].

2.2.2. Experimental conditions

To assess the degree of slag flowability in the combustion melting of sewage sludge solid fuel, the change in fluidity was measured according to the temperature of the sewage sludge, sawdust, and sawdust and sludge mixture, and basicity. The temperature was increased from 1200 °C to 1300 °C to confirm the changes in fluidity caused by temperature. In addition, the mixing ratio of sawdust was adjusted to observe the change in fluidity according to the degree of sawdust mixing. Finally, to determine the difference in fluidity according to basicity, fluidity was measured with basicity being controlled by adding CaO and SiO₂ reagents to the sewage sludge and the sewage sludge pellets. Table 1 presents the conditions of the PI test experiment.

Table 1. Pouring index test experimental conditions.

	Sawdust Mixing Ratio (%)	Temperature (°C)	Reagents Added	Basicity (-)
Test 1	0, 32 *, 100	1200, 1250, 1300	-	-
Test 2	0, 12.5, 32 *, 80, 90, 100	1300	-	-
Test 3	-	1300	SiO ₂ , CaO	0.4–2.0

* Sawdust mixing ratio 32% for sewage sludge pellets.

2.3. Pilot Plant Experiment

2.3.1. Experimental Method

The 2 ton/day scale combustion melting pilot plant consists of solid fuel supply, combustion melting, slag discharge, and combustion gas cleaning facilities, as well as oxidant supply cleaning, water cooling and recirculation, and combustion gas emission systems. Figure 5 shows the composition of the pilot plant. The combustion melting furnace employs a fixed-bed type fuel melting method, comprising combustion, slagging, and homogenisation zones. Sewage sludge solid fuel is supplied in fixed quantities through

rotary valves and conveyors on the side of the combustion furnace. Oxidants, a mixture of air and oxygen in a certain ratio, branch out as primary, secondary, and tertiary oxidants and are supplied to the reaction zone. The solid fuel ash is completely melted in the slagging and homogenisation zones and then moved to the slag quencher to be rapidly cooled by water. The slag is finally outputted through the conveyor discharge system.

Figure 5. Schematic representation of the pilot-scale combustion melting plant components and processes. SNCR: selective non-catalytic reduction, ID fan: induced draft fan.

2.3.2. Experimental Conditions

The experimental conditions for the identification of the combustion melting characteristics of the sewage sludge solid fuel according to the oxygen enrichment ratio are presented in Table 2. The slagging and volume reduction rates were calculated based on the amount of slag generation, and innocuousness was confirmed through the analysis of heavy metal content and elution of slag. In addition, the characteristics of air pollutant emissions were verified through an analysis of combustion exhaust gases.

Table 2. Pilot plant test experimental conditions.

Test Condition	Equivalent Ratio(-)	Oxygen Enrichment Ratio (%)				Oxidant Distribution Ratio (%)		
		1st	2nd	3rd	Total	1st	2nd	3rd
	1.4	70	70	100	80	80	15	5

The slagging rate and the volume reduction rate are important design factors as an indicator of the raw material reduction rate in the combustion melting facility. These are expressed as follows:

$$\text{Slagging rate (\%)} = \frac{\text{Rate of slag production (kg/h)}}{\text{Mass of sewage sludge ash fed (kg/h)}} \times 100 \quad (2)$$

$$\text{Volume reduction rate (\%)} = \frac{\text{Slag volume} \left(\frac{l}{h} \right) + \text{Fly ash volume} \left(\frac{l}{h} \right)}{\text{Volume of solid fuel fed} \left(\frac{l}{h} \right)} \quad (3)$$

3. Results and Discussion

3.1. Analysis of the Physicochemical Characteristics

Table 3 lists the physicochemical properties of sawdust, sewage sludge, and sewage sludge solid fuel. The ash content of sawdust was the highest at 19.54 wt.%, and the ash content of sewage sludge was the lowest at 3.97 wt.%. The HHV of the sewage sludge solid fuel was 14.94 MJ/kg, and its sulphur component was 0.74 wt.%.

Table 3. Properties of sawdust, sewage sludge, and mixed solid fuel samples.

Properties	Sawdust	Sewage Sludge	Sludge Solid Fuel
Proximate Analysis (Wet Basis, wt.%)	Moisture	12.98	7.48
	Combustible	67.49	73.72
	Ash	19.54	18.80
Proximate Analysis (Dry Basis, wt.%)	Combustible	77.55	79.68
	Ash	22.45	20.32
High Heating Value (HHV; Dry Basis, MJ/kg)	-	15.67	14.94
Ultimate Analysis (Dry Basis, wt.%)	C	41.48	36.95
	H	4.74	4.84
	O	28.71	25.61
	N	2.63	5.27
	S	0.00	0.74

The oxide composition of the target sample was determined through X-ray fluorescence analysis (XRF) (Table 4). According to this analysis, 60% of sewage sludge ash consisted of SiO_2 , Fe_2O_3 , and CaO , and the basicity was 0.64. Approximately 75% of the sawdust ash was composed of SiO_2 , Fe_2O_3 , and CaO , with a basicity of 0.86. The greatest distinctions between sawdust ash and sewage sludge ash were that the SiO_2 and CaO contents were high, but the Fe_2O_3 content was low, and above all, P_2O_5 was almost non-existent. In addition, the basicity of solid fuel comprising sawdust and sewage sludge was 0.81, which was higher than that of sewage sludge ash but comparable to that of sawdust.

Table 4. X-ray fluorescence analysis results of sawdust ash, sewage sludge ash, and sludge solid fuel ash.

Component	Sawdust Ash (Dry Basis, wt.%)	Sewage Sludge Ash (Dry Basis, wt.%)	Sludge Solid Fuel Ash (Dry Basis, wt.%)
SiO_2	33.2	24.0	30.5
Fe_2O_3	12.9	20.7	15.2
CaO	28.4	15.4	24.6
P_2O_5	0.8	12.7	4.3
Al_2O_3	8.9	7.1	8.4
SO_3	4.6	6.8	5.3
CuO	0.1	3.3	1.0
K_2O	4.2	2.8	3.8
ZnO	0.3	2.1	0.8
MgO	1.6	1.1	1.5
TiO_2	2.3	1.1	1.9
NiO	0.1	0.6	0.2
Cr_2O_3	0.2	0.5	0.3
CeO_2	N/D	0.4	0.2
MnO	0.5	0.3	0.5

Table 4. Cont.

Component	Sawdust Ash (Dry Basis, wt.%)	Sewage Sludge Ash (Dry Basis, wt.%)	Sludge Solid Fuel Ash (Dry Basis, wt.%)
PbO	0.1	0.3	0.2
Na ₂ O	0.3	0.2	0.3
SnO ₂	N/D	0.1	0.0
BaO	0.2	0.1	0.2
SrO	0.1	0.1	0.1
WO ₃	N/D	0.1	0.0
Cl	1.0	0.1	0.7
ZrO ₂	0.0	0.1	0.0
Co ₂ O ₃	N/D	0.0	0.0
MoO ₃	N/D	0.0	0.0
Bi ₂ O ₃	N/D	0.0	N/D
Ga ₂ O ₃	N/D	0.0	N/D
Basicity (CaO/SiO ₂)	0.86	0.64	0.81

N/D: Not detected.

According to previous studies [16,23], the melting temperature of ash is lowered or raised by eutectic phenomena in accordance with the proportions of its components. Based on the results of the XRF analysis of sewage sludge and sawdust ash used in this study, a ternary system of SiO₂, CaO, and Al₂O₃ was prepared to predict the melting temperature of sewage sludge samples [9,10,16]. Among the components of sewage sludge ash, CaO, a basic oxide, and SiO₂, an acidic oxide, are the most commonly used components used to identify the melting properties, and the melting temperature is reported to be the lowest at a ratio of 1 for CaO and SiO₂ [16,19]. As illustrated in Figure 6, sewage sludge is expected to move from the 1800 °C zone to the 1400 °C zone, and the melting temperature further increases to 1600 °C in the zone where SiO₂ content increases.

Figure 6. Melting temperatures at different basicity levels (∇ : Sewage sludge, $\circ$: Sawdust).

3.2. Correlation between Ash Melting Temperature and Melting Indices

In general, the melting temperature and flowability of ash are known to be affected by the inorganic composition of the ash, such as CaO, SiO₂, Al₂O₃, Fe₂O₃, and MgO. Representative indices indirectly indicating the melting degree in accordance with the heretofore studied coal ash compositions are as follows [30].

$$\text{Base/Acid ratio} = \frac{\text{CaO}}{\text{SiO}_2} \quad (4)$$

$$\text{Silica ratio} = \frac{\text{SiO}_2}{\text{SiO}_2 + \text{Fe}_2\text{O}_3 + \text{CaO} + \text{MgO}} \quad (5)$$

$$\text{Iron/Calcium ratio} = \frac{\text{Fe}_2\text{O}_3}{\text{CaO}} \quad (6)$$

$$\text{Silica/Alumina ratio} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3} \quad (7)$$

Using these coal-based indices, the melting temperatures of the target samples in this study, namely sewage sludge, sawdust, and sewage sludge solid fuel ash, were predicted. First, using XRF and ash fusion temperature (AFT) data on coal ash by Guo et al. [31] and Namkung et al. [32], the correlation between the indices and the melting temperature was analysed, as illustrated in Figure 7. According to the analysis, the base/acid ratio demonstrates the highest correlation at an r^2 value of 0.7882, while the r^2 values of the remaining three indices are very low.

Figure 7. Correlation of coal melting indices: (a) base/acid ratio, (b) silica ratio, (c) iron/calcium ratio, (d) silica/alumina ratio.

Table 5 presents a comparison between the predicted melting temperatures using the base/acid ratio of each target sample and the actual analysed melting temperature. The predicted and analysed melting temperatures showed similar results for all samples. In

this study, the base/acid ratio was used as an index to identify the fluidity of the target samples, including sewage sludge.

Table 5. Comparison of the melting temperature prediction and analysis results.

	Expected Melting Temperature (°C)	Ash Fusion Temperature (°C)
Sewage Sludge	1255.6	1260
Sawdust	1239.5	1270
Sludge Solid Fuel	1242.8	1290

3.3. Thermo-Gravimetric Analysis–Differential Thermal Analysis

TGA-DTA analysis results are shown in Figure 8. Under a nitrogen atmosphere, the temperature was raised to 1500 °C at 10 °C/min to measure the change in mass and heating value. The melting of the sewage sludge started at 985 °C, progressed rapidly from 1159 °C, and it was completed at 1300 °C. The melting of the sawdust began at 796 °C, lower than that of sewage sludge, and progressed in earnest from 1089 °C. The melting of the sewage sludge solid fuel began at 1004 °C, the melting progressed rapidly from 1100 °C, and it was completed at 1350 °C.

Figure 8. Results of thermo-gravimetric analysis (TGA)—differential thermal analysis (DTA), derivative thermo gravimetry (DTG): (a) sewage sludge, (b) sawdust, (c) sludge solid fuel.

3.4. Results of the Pouring Index Test

3.4.1. Pouring Index as a Function of Temperature

The effects of the reaction temperature on the PIs of sewage sludge, sawdust, and their mixture (68:32) were analysed (Figure 9 and Table 6). The reaction temperatures were at 1200, 1250, and 1300 °C. The sewage sludge showed the highest PI throughout its melting temperature range, and the PIs of all three samples demonstrated a tendency to increase with an increase in the reaction temperature. The reaction temperatures of sewage

sludge, sawdust, and their mixture satisfying the fluidity standard of 60% for normal discharge of slag were approximately 1230, 1300, and 1300 °C, respectively. The PIs of samples of sawdust mixed in sewage sludge were lower than those of the sewage sludge, and comparable to those of sawdust. In other words, mixing sawdust with sewage sludge yielded negative results with respect to ash PIs.

Figure 9. Results of pouring index at different temperatures (○: Sewage sludge, ▲: Sawdust, □: Mixture).

Table 6. Images of pouring test results.

	Temperature (°C)		
	1200	1250	1300
Sewage Sludge			
Sawdust			
Mixture (68:32)			

3.4.2. Pouring Index as a Function of Sawdust Mixing Ratio

The effect of the sawdust mixing ratio on the PI of sewage sludge solid fuel was analysed (Figure 10). The mixing ratio of sawdust was set at 12.5, 32, 80, and 90%, at a reaction temperature of 1300 °C. As the mixing ratio of sawdust increased, the basicity gradually increased while the PI decreased. When the mixing ratio of sawdust exceeded 32%, little

change in PI was observed. The PI of sewage sludge solid fuel was expected to remain at approximately 60% at a basicity index of 0.8 or higher. Therefore, if sawdust was mixed at a ratio that exceeded 32% to avoid the glue-zone, thus increasing pellet formability and HHV, no significant issue was anticipated in the operation of the combustion melting system.

Figure 10. Pouring index at various sawdust mixing ratios (▲: Pouring index, ○: Basicity).

3.4.3. Pouring Index as a Function of Basicity

The effect of basicity on the PI of sewage sludge and sewage sludge solid fuel was analysed, as shown in Figure 11. Based on the results of the XRF analysis of the ash, the basicity of the sewage sludge and mixture (68:32) was 0.64 and 0.81, respectively, and was adjusted by mixing SiO_2 and CaO in the target sample according to specific ratios. The temperature was set at 1300 °C because a PI of 100% or higher was yielded at 1300 °C. When the basicity was adjusted using SiO_2 and CaO reagents in the sewage sludge, the PI tended to be lower than that of the original sample regardless of the basicity, indicating that basicity had no effect on the PI. However, the PI exhibited a slight increase at the point where the basicity increased from 1.5 to 2.0. In addition, in the case of the mixture (68:32), the PI tended to reduce sharply as the basicity dropped below 0.5, which is distinct from the effect of the mixing ratio of sawdust on the basicity index, as illustrated in Figure 10. Inorganic materials other than CaO contained in the sawdust ash are believed to affect the change in fluidity. In addition, according to previous studies [8,16,23,33], the increase in fluidity when sawdust is added to adjust the basicity is attributed to the melting temperature being lower than that of a single substance if an inorganic material contained in the ash forms a eutectic compound.

Figure 11. Results of pouring indices according to basicity (○: Sewage sludge, ▲: Mixture).

3.5. Results of the Pilot Plant Test

3.5.1. Slag Exhaust Characteristics

A pilot test was conducted to identify the characteristics of combustion melting of sewage sludge solid fuel under oxygen-enriched conditions. Based on the results of the measurement of the PI, solid fuel of the sewage sludge with a sawdust ratio of 32% was used for the pilot plant operation, at a reaction temperature of 1300 °C where the pouring index was above 60%. A slight change in the operating temperature profile of the slagging zone during the test was observed in the initial stage of the operation, but the temperature distribution was stable across a range of 1249–1374 °C, throughout all the operational stages of the plant. The average operating temperature (1328 °C) was sufficient for the stable melting of the ash.

The weight of the slag produced from the slag quencher installed at the bottom of the combustion melting furnace was measured, the result of which is shown in Figure 12. The weight of the slag fluctuated with the operation time, but the accumulated slag discharge steadily increased. The average discharge rate of slag for all operational stages was 9.8 kg/h, which corresponded to 18.0% of the sewage sludge feed rate of 54.4 kg/h. Similarly, the ash content of the sewage sludge solid fuel was 18.8%. In other words, the melting of the ash and the discharge of slag proceeded very smoothly.

Figure 12. Pilot plant slag production mass (○: Slag production, ◇: Accumulated slag production).

XRF analysis results for the basicity of the slag produced are presented in Table 7. The composition of the slag produced was similar to the results of the XRF analysis of the sewage sludge solid fuel. The average basicity was 0.88, and the PI of the slag at 1328 °C, the average melting temperature of the pilot plant, was deemed to have remained at 60%.

The slagging and volume reduction rates of the produced slag were evaluated, and the results are shown in Figure 13. The slagging rates during all the operation stages ranged from 61.85% to 97.33%, and the average slagging rate was 88.03%. In addition, the slag volume reduction rate ranged between 87.29% and 91.63%, and was 88.93% on average. The apparent density of slag was 1.45 kg/cm³, which is approximately 1.9-fold higher than the apparent density of the common bottom ash (0.75 kg/cm³) produced during combustion. From these results, the volume reduction rate through combustion melting was expected to be approximately two times higher than that through regular combustion, which may contribute to the extension of the life span of landfills by preventing the landfill of bottom ash through combustion.

Table 7. X-ray fluorescence analysis results of slag.

Component	Slag #1 (Dry Basis, wt.%)	Slag #2 (Dry Basis, wt.%)	Slag #3 (Dry Basis, wt.%)	Slag #4 (Dry Basis, wt.%)	Average
SiO ₂	24.36	26.06	25.64	25.78	25.46
Fe ₂ O ₃	24.47	17.22	19.18	19.58	20.11
CaO	19.98	22.72	23.96	23.08	22.43
P ₂ O ₅	5.60	4.57	4.84	5.45	5.12
Al ₂ O ₃	12.12	13.47	13.10	13.09	12.95
SO ₃	0.30	0.16	0.06	0.30	0.20
CuO	0.74	0.40	0.29	0.31	0.44
K ₂ O	1.32	1.65	1.98	2.50	1.86
MgO	2.28	2.62	2.60	2.56	2.52
TiO ₂	1.52	1.72	1.99	1.83	1.76
NiO	0.33	0.07	0.10	0.10	0.15
Cr ₂ O ₃	3.88	6.01	2.88	2.65	3.86
MnO	0.36	0.44	0.39	0.32	0.38
Na ₂ O	2.24	2.04	2.04	1.96	2.07
SrO	0.21	0.25	0.25	0.18	0.22
ZrO ₂	0.29	0.60	0.72	0.30	0.48
Basicity (CaO/SiO₂)	0.82	0.87	0.93	0.90	0.88

Figure 13. Results of slagging and volume reduction ratio (△: Slagging Ratio, ○: Volume reduction ratio).

3.5.2. Air Pollutants in the Exhaust Gas

To guarantee the economic feasibility of the combustion melting process using sewage sludge solid fuel, the operation was performed under conditions of oxygen enrichment at 80%, and the air pollutants present in the generated combustion gases were analysed. From Table 8, it is evident that the values of CO and SO₂ satisfied the permissible air pollution emission criteria of the Republic of Korea, but NO_x averaged at a relatively high level of

853 ppm. Nitrogen in the air supplied for the oxygen-enriched operation was converted to thermal NO_x at the high temperature of 1300 °C. To reduce the NO_x emissions contained in the exhaust gases, facilities enabling selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR) may be installed for air pollution prevention. The efficiency of SNCR generally ranges from 50% to 60%, while that of SCR ranges from 85% to 90%. However, when SNCR and SCR are installed in the combustion melting system under an oxygen enrichment condition of 80%, the atmospheric emission concentration of NO_x is estimated to be up to 34 ppm, which does not satisfy the 30 ppm standard for permissible air pollution emission criteria of South Korea, requiring further efforts to reduce NO_x .

Table 8. Air pollutant concentrations in the exhaust gas.

CO_2 (%)			CO (ppm)			NO_x (ppm)			SO_2 (ppm)		
Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
62	31	41	60	0	2	1032	677	853	0	0	0

3.5.3. Heavy Metal Analysis

Heavy metal content and elution analyses were conducted to identify the behaviour of heavy metals in slag produced during the combustion melting process of sewage sludge solid fuel. Six heavy metals were analysed: Pb, Cd, Cu, As, Cr, and Hg (Table 9). Five heavy metals (excluding Cd) were detected in the eluted solution of fly ash from the pilot plant; in the case of slag, no metals were eluted, except for Cu. These results confirmed that the slag of the sewage sludge solid fuel retained heavy metals.

Table 9. Heavy metal concentrations in various sludge, slag, and ash samples.

Sample	Unit	Pb	Cd	Cu	As	Cr	Hg
Content Analysis							
Sludge Solid Fuel Ash	mg/kg	711.57	28.24	6,737.77	24.77	1137.24	0.07
Leaching Analysis							
Fly Ash	mg/L	0.07	N/D	0.593	0.638	0.933	0.006
Slag		N/D	N/D	0.213	N/D	N/D	N/D

N/D: Not detected.

4. Conclusions

This study reviewed the applicability of CMT in the energisation of sewage sludge solid fuel. The characteristics of slagging, according to temperature, mixing ratio of sawdust, and ash basicity were analysed using the basicity index and PI.

1. The PI of the mixture was lower than that of sewage sludge, and yielded results that were similar to those of sawdust, indicating that the sewage sludge solid fuel in which sawdust was mixed had a negative effect on the PI of ash.
2. Basicity degree gradually increased, and the PI decreased as the sawdust mixing ratio increased. In addition, in view of the minimal change in the PI depending on the mixing ratio at 32% or higher, the PI for sewage sludge solid fuel is expected to remain at approximately 60% at a basicity index of 0.8 or higher.
3. The increase in fluidity when sawdust is added to adjust the basicity is attributed to the melting temperature being lower than that of a single substance if an inorganic material contained in the ash forms a eutectic compound.
4. The slagging rate of the produced slag was 88.03%, and the resulting volume reduction rate was 88.93%, indicating a volume reduction effect on the treatment of sewage sludge in the combustion furnace.
5. Analysis of pollutants in exhaust gases generated by the combustion melting pilot plant operation demonstrated that small amounts of CO and SO_2 were produced.

However, the average NO_x concentration was high (853 ppm), indicating that nitrogen was converted to NO_x in the oxygen-rich environment. Therefore, to prevent the release of NO_x, SNCR and SCR facilities need to be installed in oxygen-enriched combustion melting plants when using sewage sludge solid fuel.

6. Analysis of slag containing heavy metals in the eluted solution from sewage sludge solid fuel showed that heavy metals contained in the sewage sludge solid fuel, with the exception of Cu, were retained within the slag. This indicates that heavy metal stability in the environment is ensured in case the sewage sludge solid fuel slag is buried in landfill.

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