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Artikel Penelitian

Characteristics of Fly Ash and Bottom Ash from Incinerators at Landfill Sites

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ABSTRACT

Waste management in Indonesia, especially in big cities, faces a big challenge as the volume of waste continues to increase every year. One of the technologies used to address this problem is incineration, which is the process of burning waste to reduce its volume and generate energy. However, this process produces residues in the form of fly ash and bottom ash (FABA), which contain harmful heavy metals such as Zn, Cu, Cr, Ba, and Ni. If not managed properly, these residues can pollute the environment because they are difficult to decompose and are potentially harmful to human health and ecosystems. This study aims to analyze the physical and chemical properties of FABA to determine its potential utilization. The results showed that fly ash has a finer particle size with a higher density than bottom ash which has coarser and larger particles. Based on ASTM C618 standard, FABA belongs to class C category, which shows $SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$ content > 50%, and CaO content > 15%. FABA has the potential to be utilized in construction, where fly ash can be used as a partial substitute for cement, while bottom ash can replace sand. The utilization of FABA enables the production of environmentally friendly construction materials, such as rosters, bricks, and paving blocks, which are the result of recycling residues. Thus, the utilization of FABA also reduces the amount of residue generated by the incineration process and reduces dependence on natural raw materials, supporting the creation of a more sustainable construction industry.

Keyword: fly ash, bottom ash, physical, chemical, recycling

ABSTRAK

Pengelolaan sampah di Indonesia, terutama di kota-kota besar, menghadapi tantangan besar karena volume sampah yang terus meningkat setiap tahunnya. Salah satu teknologi yang digunakan untuk mengatasi masalah ini adalah insinerasi, yaitu proses pembakaran sampah untuk mengurangi volumenya dan menghasilkan energi. Namun, proses ini menghasilkan residu berupa fly ash dan bottom ash (FABA), yang mengandung logam berat berbahaya seperti Zn, Cu, Cr, Ba, dan Ni. Jika tidak dikelola dengan baik, residu tersebut dapat mencemari lingkungan karena sifatnya yang sulit terurai dan berpotensi berbahaya bagi kesehatan manusia serta ekosistem. Penelitian ini bertujuan untuk menganalisis sifat fisik dan kimia dari FABA guna menentukan potensi pemanfaatannya. Hasil penelitian menunjukkan bahwa fly ash memiliki ukuran partikel yang lebih halus dengan densitas yang lebih tinggi dibandingkan bottom ash yang memiliki partikel lebih kasar dan lebih besar. Berdasarkan standar ASTM C618, FABA termasuk dalam kategori kelas C, yang menunjukkan kandungan $SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$, serta kandungan CaO > 15%. FABA berpotensi dimanfaatkan dalam bidang konstruksi, di mana fly ash dapat digunakan sebagai bahan substitusi parsial semen, sedangkan bottom ash bisa menggantikan pasir. Pemanfaatan FABA ini memungkinkan produksi konstruksi yang ramah lingkungan, seperti roster, batako, dan paving block, yang merupakan hasil daur ulang residu. Dengan demikian, pemanfaatan FABA juga mengurangi jumlah residu yang dihasilkan oleh proses insinerasi dan mengurangi ketergantungan pada bahan baku alam, mendukung terciptanya industri konstruksi yang lebih berkelanjutan.

Kata Kunci: fly ash, bottom ash, fisik, kimia, daur ulang

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1. INTRODUCTION

The issue of waste management is increasingly becoming a major concern in many major cities in Indonesia, along with rapid population growth and increasing consumption of goods. The most widely applied waste management method in Indonesia, such as landfilling, faces serious obstacles because it requires a very large area of land. To overcome land limitations and improve the efficiency of waste management, various processing technologies, such as incineration, are being implemented in several landfills. This technology can significantly reduce the volume of waste and generate electrical energy. However, the incineration process also produces residues in the form of fly ash and bottom ash (FABA), which contain hazardous heavy metals and have the potential to pollute the environment if not handled properly (Krisdiansyah et al., 2024; Yuliani et al., 2022; Lu et al., 2020).

FABA produced from waste incineration has physical and chemical characteristics that need to be analyzed further, given the potential environmental impacts it causes. Fly ash is the fine ash carried by the flue gas, while bottom ash is the coarse ash left at the bottom of the incinerator. Both types of ash contain heavy metals that have the potential to contaminate soil and water if not managed properly (Lu et al. 2020). This study aims to explore the physical and chemical characteristics of FABA produced by the incinerator at Bantargebang Landfill. Through analysis involving testing of physical and chemical properties and heavy metal content in FABA, it is hoped that useful data can be obtained for the utilization of FABA that is more environmentally friendly and supports sustainable waste management policies.

2. METHODOLOGY

This study aims to analyze the physical and chemical characteristics of FA and BA produced by the incinerator of one of the landfills in Indonesia. The methodology used in this study includes several stages, namely sampling, analysis of physical and chemical characteristics.

2.1. Sampling Location

This research was conducted at one of the largest landfills in Indonesia which has been equipped with a waste management installation using Waste Power Plant (PLTSa) technology. The sampling location focused on the waste incineration process using a moving grate incinerator. The landfill manages about 100 tons of waste per day which produces fly ash in the form of fine particles carried by flue gas and bottom ash as coarse particles left at the bottom of the incinerator.

2.2. Sampling

FABA is produced from the waste combustion process in the incinerator and is collected in an open shelter, so sampling is carried out directly at the FABA production site. The sampling method used is random sampling. Random sampling is a sampling method where each population has the same opportunity to be selected as a sample (Firmansyah dan Dede 2022). Samples can be taken periodically to obtain temporal variations in ash composition. After sampling, samples are collected in a clean container to prevent contamination before analysis in the laboratory.

2.3. Analysis of Physical and Chemical Characteristics

Physical analysis is conducted to evaluate the basic properties of FABA, including measurements of moisture content, ash content, volatile content, specific gravity, volume weight, void ratio, porosity, degree of saturation, sieve analysis, and morphology. Meanwhile, chemical analysis involves pH measurements to assess acidity or basicity, testing for heavy metal content using Atomic Absorption Spectrophotometry (AAS), and identification of metal oxides by X-ray fluorescence (XRF). Characteristic and chemical analysis followed standards such as SNI and ASTM.

3. RESULTS AND DISCUSSION

3.1. Operational Evaluation of Incinerator at Landfill

The operational evaluation of the moving grate incinerator at the landfill shows that although the incineration system runs continuously with a stable processing capacity, there are still technical aspects that are not optimal.

One of them is the management of FABA which has not been supported by adequate handling and storage facilities. FABA residues left in open spaces without cover risk environmental pollution and cause problems in the long run. In addition, the absence of advanced utilization or residue processing systems indicates that the approach to secondary waste from incineration has not been fully integrated in the overall waste management system.

3.2. Analysis of Physical and Chemical Characteristics of FABA

3.2.1. Physical Characteristics

The results of the physical characteristics analysis of FABA show variations in physical properties between the two ash types. The physical characteristics of FABA can be seen in Table 1.

Table 1. Inspection Results of Physical Characeristics of FABA

Parameters	Results		Standard Method Testing	Sand Specifications (SNI 03-6882 2002)	Cement Specifications (SNI 15-2049, 2004; ASTM C150-20, 2020)	Previous Research			
	Fly Ash (%)	*Bottom Ash* (%)				*Fly Ash* (%)	*Bottom Ash* (%)	Type	Reference
Water content (%)	0,02	33,30	ASTM D2216-19	Maks. 5%	Maks. 1%		37-42	Furnace of coal fired thermal power plant	Kumar (2015)
Ash content (%)	92,40	58,77	ASTM D 3174-2004	-	-	5-95	45-50	Moving grate incinerator	Blasenbauer et al. (2023)
V*olatile content* (%)	6,47	7,64	ASTM D 3175-20	-	-		5-7	Moving grate incinerator	Lu et al. (2020)
Specific gravity	2,46	2,48	ASTM D854-23	2,60 – 2,80 kN/m^3	3,10 – 3,15 g/cm^3	,86	1,77	Thermal power station	Reddy et al. (2018)
Bulk density (%)	30,42	42,23	ASTM D7263-21	-	-	0-35	40-45	Moving grate incinerator	Lu et al. (2020)
Void ratio (e)	2,29	1,37	ASTM D7263-21	1 - 1,2	-		-	-	-
Porosity (n)	0,70	0,58	ASTM D7263-21	0,30 – 0,50	-		-	-	-
Saturated deg (%)	2,52	80,86	ASTM D7263-21	-	-		-	-	-

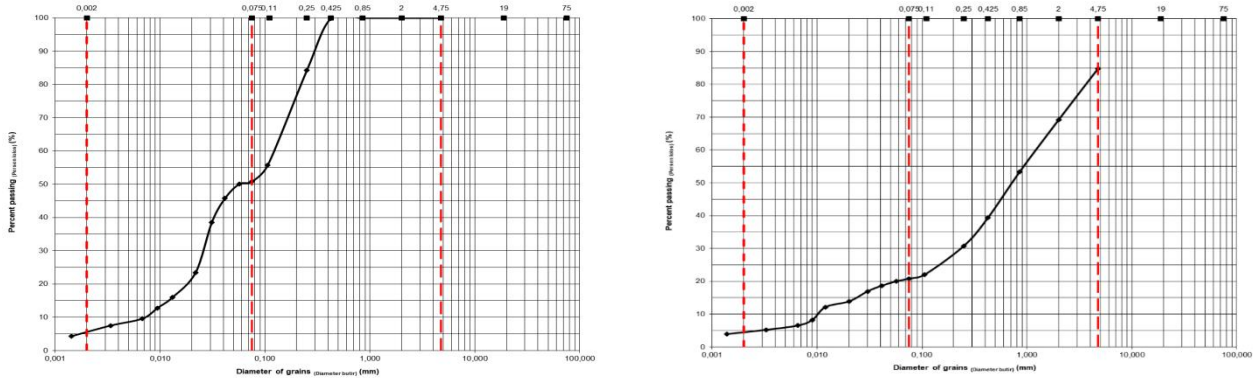
Based on the results in Table 1, FA has a very high ash content and very low moisture content, reflecting excellent combustion efficiency, as almost the entire material is degraded into lighter fine ash. FA also has a high void ratio and greater porosity, making it more hollow and suitable for applications where lightweight materials are required. In contrast, BA has denser characteristics and absorbs more water, with a lower void ratio and smaller porosity, making it more suitable for construction applications that require denser and more stable materials, such as aggregates. These results are relatively in line with the findings in the studies of Blasenbauer et al. (2023) and Lu et al. (2020) which showed that FA from moving grate incinerators tend to have lighter and finer properties, while BA is denser and contains more water.

Comparison with other combustion technologies such as furnaces of coal fired thermal power plants and thermal power stations shows significant differences in ash characteristics. In coal fired thermal power plants, FA has a lower ash content and different volatile matter content due to the combustion process using coal. Research conducted by Reddy et al. (2018), FA from thermal power plants has a lower specific gravity of 1.86 compared to a moving grate incinerator of 2.46-2.48, indicating a difference in the composition of the ash produced. In addition, in thermal power stations, which use fossil fuels such as coal or gas to generate electricity, the ash produced also has different characteristics depending on the fuel used, with FA containing more heavy metals.

In addition, the FABA sieve analysis test results and sieve analysis graphs can be seen in Table 2 and Figure 1.

Table 2. FABA Sieve Analysis

Sieve Number	Diameter (mm)	Cumulative Passing Percentage		Specification ASTM C33/ C33M
		Fly Ash	Bottom Ash	
4	4,75	100,00	84,77	95-100
10	2,00	100,00	69,17	80-100
20	0,85	99,99	53,33	50-85
40	0,43	99,90	39,37	25-60
60	0,25	84,22	30,77	5-30
140	0,11	55,70	22,04	0-10
200	0,075	50,79	20,81	0
Total		590,61	320,25	-
PAN		50,79	20,81	-
Fineness Modulus		1,09394	3,79752	-



(a) Fly Ash (b) Bottom Ash

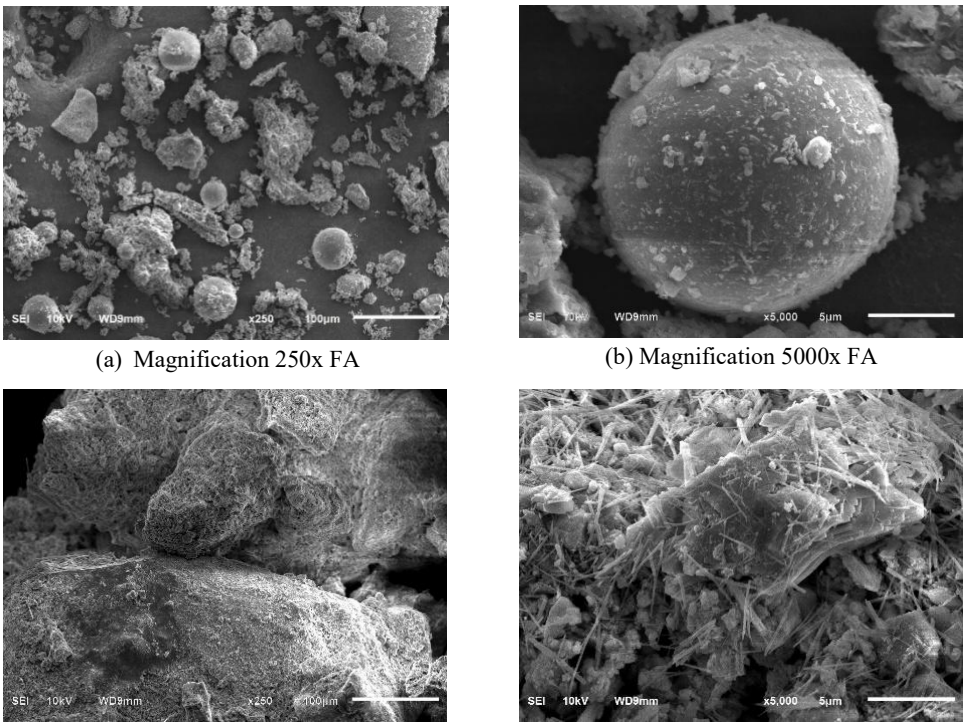
Figure 1. Sieve Analysis Graph

Based on Table 2 and Figure 1, it can be seen that fly ash has a finer particle size distribution, with most particles passing through sieves smaller than 2 mm. At the 4.75 mm sieve, fly ash has 100% of the particles passing, but after the 200 mesh (0.075 mm) sieve, only about 50% of the particles pass. This shows that fly ash is mostly composed of fine particles that have a size smaller than 0.25 mm. In contrast, the particle size distribution of bottom ash shows a larger size variation. At the 4.75 mm sieve, almost 85% of the particles pass, indicating the presence of many large particles in the bottom ash. As the sieve size decreases, the percentage of particles passing decreases significantly, with only about 20% of particles passing at the 0.075 mm sieve.

According to a study conducted by Yu et al. (2013), showed that the particle size of BA varies widely, ranging from fine powder to more than 4.75 mm, which is consistent with the fact that BA is a heterogeneous material containing concrete, ceramics, glass, bricks, some metals, and melted particles. BA can be classified into fine (<0.18 mm), medium (0.18-1.4 mm), and coarse (>1.4 mm) particles. Meanwhile, the particle size distribution of FA is likely to be in the range between 2 to 300 μm, with an average volume-based particle size of 112.3 μm; more than 90% of the particles are smaller than 197.39 μm. It is also observed that, coarser sized FA are generally formed due to fragmentation and elutriation. While fine particles are formed through solid-vapor-particle processes such as vaporization, nucleation, condensation, and coagulation.

Based on the analysis, FA can be used as a substitute for cement in concrete mixtures because it has a fine particle size, a very low moisture content of 0.02% and a high ash content of 92.40%, which provides a strong bonding ability in mortar (Pramudya, Abu Hasan, dan Robert Junaidi 2024). FA also has a high void ratio of 2.29 and porosity of 70%, which enables it to improve mortar workability and provide a pozzolanic effect that increases the

long-term strength of concrete, while reducing portland cement consumption (Zaki dan Atis 2020). Meanwhile, BA with its coarse particle size distribution and lower ash content of 58.77%, is more suitable for use as a sand substitute in concrete mixes. BA has a high volume weight of 42.23% and a fineness modulus of 3.79752, indicating that it is denser and more stable, providing good mechanical strength to the concrete mix (Kardiman, Sabaruddin, dan Gaus 2022). BA also has a high degree of saturation of 80.86% and a lower porosity of 58%, which provides more stability to the concrete mix, although it requires more water adjustment to prevent segregation (Putri et al., 2023).



(a) Magnification 250x FA (b) Magnification 5000x FA

c) Magnification 250x BA (d) Magnification 5000x BA

Figure 2. SEM Test Results

Figure 2 is the SEM test result of FABA. Morphological observation of FABA was carried out using a Scanning Electron Microscope (SEM). The SEM results show that FA has a smoother and more brittle surface, with many small spherical particles indicating that the ash was carried away by the flue gas in the incineration process. The FA particles also appear more uniform in size and shape. On the other hand, BA shows a coarser and more textured morphology, with many larger and irregularly shaped particles. SEM showed that the particles in BA were denser and larger in shape, with some aggregates appearing to coalesce, reflecting its denser and larger physical properties compared to FA. Based on the morphology of FABA in this study, in line with research conducted by Annisa Shabrina (2020), that the shape and fineness of FA and BA particles greatly affect the porosity and density of concrete, the more rounded and regular the shape of FA and BA particles, the smaller the shaft formed so that the concrete becomes denser and stronger. However, FA and BA with irregular and coarse particle shapes can cause porosity and low concrete density. This can lead to a decrease in the compressive strength of the concrete.

3.2.2. Chemical Characteristics

a. pH Testing

The test results show that the pH of FA is 7.90, while that of BA is 7.97. Both are in the neutral range, which meets the requirements in construction material standards. These results are comparable to the studies conducted by Rusănescu & Rusănescu (2023) and Alam et al. (2021), also showing that the pH of FABA is generally in the neutral or slightly alkaline range. In their studies, the pH of the tested FA was in the range of 7.56 - 8.09. Based on ASTM C618, neutral or slightly alkaline pH values favor applications in concrete mixtures, especially to prevent corrosion of steel reinforcement.

b. Heavy Metals and Metal Oxides

Characterization of heavy metals and heavy metal oxides present in FABA solid waste is by using X-Ray Fluorescence (XRF) chemical instrument, the results can be seen in Table 3 and Table 4.

Table 3. Heavy Metal Content in FABA

Parameters (mg/kg)	Results		Maximum Level Government Regulation Number 22 of 2021	
	Fly Ash	*Bottom Ash*	TCLP-A (mg/L)	TCLP B (mg/L)
As	1,897	1,714	3	0,5
Ba	24,822	39,931	210	35
Cu	94,415	86,673	60	10
Zn	337,138	433,949	300	50
Pb	0,781	0,778	3	0,5
Ni	12,237	11,235	21	3,5
Se	8,82	9,242	3	0,5
Co	1,345	1,313	200	-
Ag	3,081	3,21	40	5
Sn	<0,22	<0,22	2	-
Hg	0,076	0,071	0,3	0,05
Cr	66,915	58,079	15	2,5
Cd	1,272	1,006	0,9	0,15
Mo	<0,13	<0,13	21	3,5
CN	<0,5	<0,5	21	3,5
F	0,746	0,655	450	75

Table 3 shows that the concentration of heavy metal elements in FABA varies. In FABA, there is an abundance of major elements in the order of Zn > Cu > Cr > Ba > Ni > Se > Ag > As > Co > Cd > Pb > F > CN > Sn > Mo > Hg. The dominant elements identified in FABA are Zn, Cu, Cr, Ba, and Ni. The lowest element is Hg. Heavy metal concentrations in FABA show differences between FABAs, with some heavy metals showing a tendency to be higher in FA, while others are more abundant in BA. For example, Cd and Pb were higher in FA compared to BA, possibly due to the evaporation of these metals which condensed and aggregated on the FA surface due to the lower temperature in the flue gas cooling system (Gao et al., 2024). This table also shows that the heavy metals in FABA are still within the limits set by Government Regulation Number 22 of 2021.

Table 4. Metal Oxide Content of FABA

Parameters	Results (%)		Comparison with Other Countries*							
	Fly Ash	*Bottom Ash*	*Fly Ash*				*Bottom Ash*			
			China	Portugal	Jepang	Perancis	China	Portugal	Jepang	Perancis
SiO_2	34,55	43,45	19,81	3,25	12,01	27,23	55,2	43,75	49,3	37,78
Al_2O_3	12,07	11,20	6,79	2,31	8,1	11,72	9,6	6,81	7,5	11,88
Fe_2O_3	5,02	6,38	4	0,39	1,21	1,8	5,7	2,03	7,6	8,01
CaO	23,41	18,12	23,63	38,7	13,86	16,42	15,9	22,77	16,3	23,29
MgO	2,77	2,65	3,78	1,67	2,62	2,52	2,6	5,11	2,6	3,87
K_2O	2,48	2,32	6,23	8,35	7,41	5,8	1,7	3,12	1,1	1,63
Na_2O	2,78	2,88	6,68	11,57	17,19	5,86	5,1	7	6	3,7
TiO_2	2,97	1,20	-	-	-	-	-	-	-	-
LOI	9,51	10,87	-	-	-	-	-	-	-	-

*source: (Lu et al. 2020).

Table 4 presents the results of the analysis of metal oxide content in FABA produced from the combustion process. The parameters analyzed include the content of major metal oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, TiO_2, and LOI (Loss on Ignition). The study conducted by Lu et al. (2020) in the form of a comparison of the metal oxide content of FABA with other countries, such as China, Portugal, Japan, and France, showed differences in the content of each oxide. For example, in this study FA had higher concentrations compared to other countries, while other oxides showed varying results between each country. This reflects differences in the composition of the waste burned as well as the combustion technologies used in different countries.

Based on ASTM C618, the FABA of Bantargebang Landfill belongs to Class C because it has $SiO_2 + Al_2O_3 + Fe_2O_3$ >50% and CaO >15%. With this condition, the ash from this combustion can be utilized as the manufacture of readymix concrete products, paving blocks, concrete blocks, conblock, lightweight bricks, precast products, namely wave breakers, canstin, and other similar precast products, other products for civil infrastructure. According to Asof et al., (2022), FA is a suitable material used as a substitute for cement and BA is a suitable material as a partial substitute for sand in concrete mixtures.

4. CONCLUSION

Based on the research results, FABA contains organic and inorganic components, heavy metal elements, metal oxide compounds, and has physical and chemical characteristics that support its utilization in the construction industry. FA with its fine particle size, high ash content, and large porosity can be used as a substitute for cement in concrete mixtures. Meanwhile, BA with its coarser particle size distribution and denser nature is suitable for partial substitution of sand in concrete. Both types of ash contain heavy metals, but the levels of heavy metals are still within the permissible limits according to Government Regulation Number 22 of 2021 concerning the Implementation of Environmental Protection and Management. Thus, FABA can be utilized to produce environmentally friendly construction products. The use of FABA not only reduces residues, but also reduces dependence on natural raw materials, supports the sustainability of the construction industry, and creates more environmentally friendly construction materials.

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