Effect of power plant operating conditions on fly ash and bottom ash composition: a case study from power plant in Lampung

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Abstract. Fly ash and Bottom ash (FA-BA) are solid waste produced from the coal-generated power plant. FA consists of fine powder particles with diameters varying from 0.5-100 µm, while BA consists of coarser particles with a diameter of 0.125-2 mm. FABA and feed coal samples were collected from the power plant in Lampung to distinguish the effect of power plant operating conditions on FABA composition. Feed coal characteristics were examined by proximate and petrography analysis. Organic and inorganic components of FABA were identified using petrography analysis, while the detailed mineralogical composition of FABA was determined using X-Ray diffraction analysis. Moreover, major oxides of the feed coal and FABA were determined using inductive ICP-AES. From the analysis, it was found that FA composition is mainly organic material in the form of unburned carbon (UC). The abundance of UC content (up to 74.68%) indicates the inefficiency of the coal combustion process. In terms of inorganic, quartz is the most abundant mineral found in the FABA sample, up to 50.15%, in contrast to the glass content that was only 17.41%. A minor amount of spinel (0.03-2.00%) was found associated with Fe-oxide mineral. Kaolinite was only found in the BA sample from a landfill source and interpreted as external input from the dumping ground. The high content of UC and quartz will decrease the compressive strength of the material construction product providing a negative impact on the utilization of FABA.

1. Introduction
Fly ash is fine solid powders that remain after the coal combustion in a power plant recovered from an electrostatic dust filter [1]. FA particles generally have a spherical shape with a diameter ranging from 0.5-100 µm. BA consists of coarser particles (0.125-2 mm) than FA concentrated at the bottom of the furnace after combustion [1]. Based on Indonesia government regulation No. 11 Year 2014, FABA is classified as hazardous waste and toxic material, which has many mandatorises of treatment and permits
that must be completed [2]. Indonesia’s power generation produced 4.38 million tons of FABA in 2015 and 166.2 million tons in 2019 [2]. Aside from the abundance of FABA, the characteristic will be undoubtedly essential to determine the potential utilization. FABA characteristics are affected by several factors. One of them is the coal-burning technology applied in the power plant. The technologies are Fluidized Bed Combustion (FBC) and Pulverized Coal Combustion (PCC). The main difference between those technologies is in the feed coal particle size in which powder is applied in the PCC technology. The characteristics of FBC-FABA are different than PCC-FABA, generally because of the wide variety of fuel mixtures, additive possibilities, combustion temperatures, boiler technology, and ash collection technology [3]. Previous studies on FABA compositions were limited to a power plant in Java, Indonesia [4]. This study will provide information and comprehensive discussion about the effect of operating conditions of a power plant on FABA characteristics.

2. Materials and Method
FABA and feed coal samples were collected in 2019 from Power Plant located in Lampung, Indonesia (see Figure 1). Sixteen samples of FA, six samples of BA, and two samples of feed coal were examined in this study (Table 1). The FA samples were collected directly from the silo, electrostatic precipitator (ESP), and landfill source, while BA samples were collected directly from the coal ash handling equipment and landfill. All samples were sealed in plastic bags and tightly closed to avoid contamination.

| Sample | Type     | Source                   |
|--------|----------|--------------------------|
| FA-1   | Fly Ash  | Silo                     |
| FA-2   | Fly Ash  | Silo                     |
| FA-3   | Fly Ash  | Electrostatic Precipitator (ESP) |
| FA-4   | Fly Ash  | Landfill                 |
| FA-5   | Fly Ash  | Landfill                 |
| FA-6   | Fly Ash  | Landfill                 |
| FA-7   | Fly Ash  | Landfill                 |
| FA-8   | Fly Ash  | Landfill                 |
| FA-9   | Fly Ash  | Landfill                 |
| FA-10  | Fly Ash  | Landfill                 |
| FA-11  | Fly Ash  | Landfill                 |
| FA-12  | Fly Ash  | Landfill                 |
| FA-13  | Fly Ash  | Landfill                 |
| FA-14  | Fly Ash  | Landfill                 |
| FA-15  | Fly Ash  | Landfill                 |
| FA-16  | Fly Ash  | Landfill                 |
| BA-1   | Bottom Ash | Fresh                  |
| BA-2   | Bottom Ash | Landfill               |
| BA-3   | Bottom Ash | Landfill               |
| BA-4   | Bottom Ash | Landfill               |
| BA-5   | Bottom Ash | Landfill               |
| BA-6   | Bottom Ash | Landfill               |
| C-1    | Feed Coal | Coal Feeder            |
| C-2    | Feed Coal | Coal Feeder            |

Table 1. List of samples collected from the study area.
Several analyses were conducted on this study to examine the effect of power plant operating conditions on FABA compositions as follows:

2.1. Proximate Analysis
Proximate analysis was conducted to evaluate ash yield, volatile matter, moisture content, and fixed carbon based on ASTM [5] in the laboratory of the Center for Mineral, Coal, and Geothermal Resources, The Ministry of Energy and Mineral Resources, Indonesia. The calorific value of feed coal was evaluated based on ASTM [6].

2.2. Geochemistry Analysis
Major oxides of FABA and feed coal samples were examined using inductively coupled plasma – atomic emission spectroscopy (ICP-AES) by ALS Geochemistry Laboratory, Kamloops, Canada.

2.3. Petrography Analysis
Polished blocks of feed coal and FABA samples were made using SpeciFix-20 Kit and Struers Labo System tools. Coal petrography was conducted based on the Standard Test Method for microscopical identification of maceral compositions [7]. Maceral classification followed the ICCP System 1994 [8-10] (ICCP, 2001; Sýkorová et al., 2005; Pickel et al., 2017). Organic and inorganic components of FABA were identified using genetic classification [11-12]. All petrography analysis were conducted in the Department of Geological Engineering, UGM.

2.4. Mineralogy Analysis
X-Ray Diffraction (XRD), Panalytical E’xpert 3 Powder, analysis was conducted for the detailed mineralogical composition of FABA. Bulk XRD analysis was performed with 2θ from 2° to 60° and a scanning step of 0.02 in 2θ (degree) in the analytical laboratory of the Indonesian Institute of Sciences (LIPI), Lampung, Indonesia. XRD analysis could reveal the mineralogical transformation due to coal combustion in the power plant.

3. Results

3.1. Feed Coal Properties
Feed coal from the Power Plant has ash (A) yield in the range of 9.80-9.89 wt.%, moisture (M) contents of 24.40-24.50 wt.%, volatile matter (VM) of 32.69-32.96 wt.%, fixed carbon (FC) content of 32.65-33.11 wt.% while the calorific value (CV) is in the range of 4616-4630 cal/gr (Table 2).
Table 2. Result of proximate analyses (wt.%) and calorific values (cal/gr) for feed coals from the study area.

| Sample | $M_{\text{adb}}$ | $A_{\text{adb}}$ | $V_{\text{adb}}$ | $F_{\text{adb}}$ | $CV_{\text{adv}}$ (Cal/gr) |
|--------|-----------------|-----------------|----------------|----------------|-----------------------------|
| C-1    | 24.40           | 9.80            | 32.69          | 33.11          | 4630                        |
| C-2    | 24.50           | 9.89            | 32.96          | 32.65          | 4616                        |

3.2. Organic and Inorganic Composition of Feed Coal and FABA

From the petrography, it can be seen that the feed coal samples are rich in vitrinite (66.00-70.30%, Table 3), while liptinite content is in the range of 15.65-21.40%. Inertinite is about 10.60-10.75%, and minerals matter from 2.00-3.30%. The main composition of mineral matter of feed coal is clay mineral, pyrite and quartz are also observed but in lower quantity (Figure 2).

Table 3. Feed coal compositions based on petrography analysis (%; vol).

| Sample | Vitrinite | Liptinite | Inertinite | Mineral Matter |
|--------|-----------|-----------|------------|----------------|
| C-1    | 66.00     | 21.40     | 10.60      | 2.00           |
| C-2    | 70.30     | 15.65     | 10.75      | 3.30           |

Figure 2. Percentages of coal mineral matter normalized to 100%.

Petrography analysis indicated that FABA samples consist of organic and inorganic components (Figure 3). Organic material presents in the form of unburned carbon (UC) with dark grey or black color. Inorganic components of FABA were identified as crystalline phase minerals and amorphous material. Amorphous material occurred as Glass. Glass based on their morphology variations can be identified as cenosphere and pleisosphere. Glass characterized by perfectly or not-perfect spherical form with light grey-dark grey color under reflected light examination. The crystalline phase mineral of FABA consists of quartz, fe-oxide minerals, and spinel. Quartz is identified as an angular-subrounded form with colorless or white color. The fe-oxide mineral is characterized by orange-red color with an angular-subangular shape. At the same time, spinel generally occurs as angular crystals with a dendritic texture associated with Fe-oxide minerals.
Figure 3. Reflected light photomicrographs of different FABA samples: A.) FA-Silo; B.) FA-Landfill, C.) FA-ESP, D.) BA-Landfill. Qz: Quartz; UC: unburned carbon.

UC dominates FA composition with abundance in the range of 40.00-74.68%. The other components occur from 16.98-43.94% for quartz, 4.85-15.45% for Glass, 0.38-2.00 for Fe-oxide minerals, and 0.04-0.08% for spinel. Different compositions trends showed in BA samples (see Figure 4). BA compositions are dominated by quartz with abundances in the range 49.03-50.15%. The other compositions occur varies from 32.34-33.45% for UC, 16.85-17.41% for glass, 0.34-0.49% for Fe-oxide minerals, and 0.03-0.05% for spinel.

Figure 4. Percentage of organic and inorganic components on FABA. UC=unburned carbon.

3.3. Mineralogy Composition of FABA

Bulk XRD analysis was only conducted for six FABA samples (Figure 5). The diffractogram shows that FABA samples have a major peak of quartz minerals (Figure 6). Mineralogy variations based on XRD analysis were identified as quartz, hematite, pyrite, calcite, plagioclase, and kaolinite. Kaolinite only occurs in BA samples from landfill sources. Results of XRD analysis indicated that quartz content in
FA samples is higher than in BA, while plagioclase content in FA was lower than BA samples (Figure 5).

**Figure 5.** Mineralogical compositions of FABA.

**Figure 6.** Detail mineralogical identification of sample FA-5 based on XRD analysis.
3.4. Feed Coal and FABA Geochemistry
The main major oxides of feed coal and FABA samples are SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, and CaO (see Figure 7). The most dominant major oxide both in feed coal and FABA is SiO$_2$ (≥55%). The dominant major oxides content (SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, and CaO) in the coal is generally related to clay mineral, quartz, and pyrite minerals abundances. The abundances of inorganic components found in FABA, including quartz, Glass, hematite, pyrite, spinel, plagioclase, calcite, and kaolinite, also correlate with dominant major oxides' content the FABA samples (SiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, and CaO).

![Figure 7. Major oxides content of feed coal and FABA samples.](image)

3.5. Power Plant Operating Condition
The Power Plant of the study area uses circulating fluidized bed combustion (CFB) technology and has a capacity of 2×8 MW (MegaWatt), which uses limestone to desulfurize while operating and uses quartz sand particles (<1.49 mm) as bed material. It consumes about 50 tons of coal per hour. FABA samples were collected when the power plants were operating under normal conditions. The operating temperature was set to 850°C, the steam temperature at 470°C, and the steam pressure at 4.9 Mpa. The type of coal feeder system was used in this plant is a screw feeder system with the feed coal size specification ranged between 2-5 mm.

4. Discussion
The characteristics of FABA components are generally controlled by the feed coal characteristic, boiler, and operating conditions [13]. FA composition from the study area was dominated by organic material in the form of UC. The abundances of UC content (up to 74.68%) indicate inefficiency in the coal combustion process. UC in coal ash was produced from incomplete combustion of origin coal.
The occurrence of UC is caused by the rank and maceral composition of the coal and other factors such as combustion technology, off-spec feed coal particle size, and the use of unsuitable feed coal composition [12]. Feed coal plays a significant role in controlling the amount of carbon burnout, with increased carbon burnout being important for increased boiler efficiency [12]. A high proportion of >150µm feed coal particle decreased carbon burnout and negatively impacted efficiency [14]. According to Ganguli and Bandopadhyay [15], the higher the coal particle size < 76 µm, the higher the power plant efficiency. Referring to the specification of pulverized feed coal used in the Power Plant in the size of 2-5 mm (coarse particle), the inefficiency of coal-burning will most likely occur, leading to decrease the plant efficiency, and caused the abundance of UC formation in FA sample. That is why in the FCC technology, the burning efficiency is lower than that of the PCC due to the bigger particle size distribution of the feed coal. In addition, affecting the character of the FA resulted in higher unburned carbon content in the FCC.

Inorganic components of FABA from the study area were mainly composed of crystalline phase minerals, in contrast to pulverized coal combustion (PCC) FABA from Java, mainly consisting of spherical amorphous materials or Glass [4]. This difference is due to the lower operating temperature of CFB technology (700-900°C) compared to PCC technology at 1300-1700°C; this condition caused FBC boiler temperature is not enough to melt all inorganic particles [3]. The lower operating temperature condition in the study area resulted in the abundance of quartz up to 50.15%, in contrast to Glass produced during combustion is only 17.41%. Amorphous material or Glass was found less abundant in ashes from FBC than from pulverized-coal plants, mainly due to the lower operating temperature [12]. Quartz is the most abundant mineral found in the FABA sample from the study area. Quartz is the most common mineral pass through the coal combustion because it does not melt when heating at a temperature below 1400-1500°C [11-12]. Inside the CFB boiler, sand beds were floating together with fuel on a forced high-velocity airflow [3]. The function of bed material is to improve heat transfer and reduce temperature gradients [3]. Application of bed material using sand that was not suitable for the boiler affected the abundant quartz and resulted in less plagioclase on FABA components.

Fe-oxide mineral in FABA samples was identified as hematite. Fe-oxide minerals in FABA samples are produced from coal combustion, rich in Fe [16], while Fe-bearing mineral in origin feed coal sample presents as pyrite. Pyrite starts to decompose at around 400-500°C and produces the main product of iron oxide minerals such as hematite and magnetite [17]. A minor amount of pyrite found in the FABA sample varies from 1.76-3.64%. A minor amount of spinel (0.03-2.00%) was found associated with Fe-oxide mineral. Spinel is a secondary iron mineral produced from the decomposition of Fe sulfides and other Fe-bearing minerals in the coal [11]. Mineralogy of CFB FA is often complex due to limestone or dolomite as an in situ desulfurizing agent [12]. Calcite in the FABA sample was interpreted as the natural origin from coal mineral matter or as a secondary source related to limestone input during the combustion process. Kaolinite is only found in the BA sample from landfill sources and interpreted as external input from the dumping grounds.

5. Conclusions
UC dominates the composition of FABA from the study area up to 74.68%. In contrast, the maximum Glass produced is only 17.41%, while quartz content is up to 50.15%. It indicates inefficiency in the coal combustion process that may be due to applying the bed material that is not suitable for the boiler and/or the coal feed size. The higher UC and quartz and lower glass content will reduce the potential utilization of FABA as the raw material of construction.

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