Assessment of Kalimantan Coal Ash Properties and Potential as Sustainable Construction Material

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ABSTRACT

This study analyzes the physical and chemical characteristics of Fly Ash and Bottom Ash (FABA) from Kalimantan's coal-fired power plants to assess their effectiveness and potential as sustainable construction materials. The characterization was conducted through a series of tests following ASTM C311 standards, while the mechanical properties of mortars incorporating Fly Ash (FA) were evaluated following ASTM C618 standards. The results indicate that all FA samples meet the ASTM C618 Fineness requirements, with particle sizes below 45 µm, confirming their suitability as pozzolanic materials. In contrast, Bottom Ash (BA) samples do not meet the Fineness standard but still show potential for use in other construction applications. Chemical analysis utilizing X-ray Fluorescence (XRF) further supports the potential use of FABA from Kalimantan, revealing a high content of reactive oxides, SiO_2, Al_2O_3, Fe_2O_3, which justify the classification as Class F for PLTU Asam-Asam (AA) and PLTU Bengkayang (BK), and the classification as Class C for PLTU Pulang Pisau (PP). X-Ray Diffraction (XRD) analysis also validates the high silica (SiO_2) content and low levels of deleterious compounds. Additionally, the mechanical properties confirm the effectiveness of FA from PLTU AA with a Strength Activity Index (SAI) value exceeding 100%. The findings of this research provide strong evidence for the potential of Kalimantan FABA as a sustainable material while contributing to enhanced compressive strength and durability in concrete application.

Keywords-sustainable construction material; Kalimantan FABA; XRF; XRD; SAI

I. INTRODUCTION

The cement sector accounts for over 7% of global carbon dioxide (CO_2) emissions [1]. Despite this significant impact, cement remains a major construction material. The primary source of CO_2 emissions in the cement industry is the production of clinker [2]. In 2018, cement production generated 2,059 Mt of CO_2 emissions, with projections indicating an increase to 4.246 Mt by 2050 [3]. Additionally, the growing demand for cement is expected to have increased Indonesia's CO_2 emissions by up to 200% by 2050 [3]. Strategies to mitigate CO_2 emissions from the cement industry are urgently needed. One approach that can be applied is the utilization of Carbon Capture and Storage (CCS) technology [3, 4]. However, this technology still requires high costs [4]. Alternatively, the utilization of Supplementary Cementitious Materials (SCMs) from industrial or agricultural waste is a better cost-effective option for reducing CO_2 emissions [5-9]. SCMs can be incorporated as a mineral mixture in the cement clinker production process to produce blended cement [4, 10, 11]. In addition, SCMs are also used as a substitute or additive of cement in concrete mixtures and in geopolymer concrete

[12-19]. The most common SCM utilized is coal ash, which includes FABA that are by-products of coal-fired power plants.

Regarding its availability, approximately 700 million tons of industrial waste is annually produced worldwide, with 70% of it being FA [20]. Indonesia, which is primarily supplied with electricity from coal-fired power plants, also has abundant FABA availability. In addition, the Indonesian State Electricity Company (PT. PLN) plans to have added new power plants in Kalimantan with a capacity of up to 550 MW by 2030 [21]. Thus, around 9 to10 million tons of coal are estimated to be annually needed [21]. If approximately 5% of FABA is generated from coal combustion, 0.45 million tons of FABA waste will be annually produced [22]. The effectiveness of FABA, particularly FA, as SCMs depends on several factors, including their chemical composition, phase (crystalline and glassy), the proportion of the glassy phase (Al, Si, Ca, Fe, Mg, Na, and K), coal combustion temperature, and their surface area [23]. The characteristics of FABA are influenced by various factors, such as the coal type, namely anthracite, bituminous, subbituminous, and lignite, combustion conditions, and collection system [24, 25]. Several studies of FA waste from AA coal-fired power plants have shown variations in the proportion of chemical compositions [13, 26, 27]. A similar phenomenon can be also observed in FA waste from other coal-fired power plants [28]. According to ASTM C618, the chemical composition of FABA will determine their classification, class N, C, or F, with each classification giving different effects of FA as an SCM [29]. Consequently, the challenge in utilizing FABA lies in ensuring a stable supply and maintaining a relatively consistent characteristic [30]. Therefore, it is important to analyze the physical and chemical characteristics of Kalimantan FABA to certify its effectiveness and potential as a sustainable construction material.

II. MATERIALS AND METHODS

A. Materials

This study utilized Portland Composite Cement (PCC) from the Cement Industry. The FABA were obtained from three different coal-fired power plants in Kalimantan, which are PLTU AA, PLTU PP, and PLTU BK. Considering the fine aggregates, sand attained from the Barito River in South Kalimantan was used. Figures 1 and 2 illustrate the FABA utilized in this study.

Fig. 1. FA sampel from (a) PLTU AA, (b) PLTU PP, and (c) PLTU BK.

Fig. 2. BA sample from (a) PLTU AA, (b) PLTU PP, and (c) PLTU BK.

B. Methods

The determination of Kalimantan's FABA characteristics was conducted through a series of tests under ASTM C311 [5, 31-35]. The assessments of FABA characteristics were categorized into three groups:

1. Physical Properties

Regarding Physical Properties, the tests carried out were the Fineness test and Particle Size Distribution. All samples were first prepared by having been passed through a number 200 sieve before testing.

2. Chemical Properties

Tests, such as Moisture Content, Loss on Ignition (LoI), and Chemical Composition Analysis, were conducted using XRF and XRD. For the chemical investigation, all samples were prepared by having been sieved through a number 200 sieve.

3. Mechanical Properties

Furthermore, tests related to the mechanical properties of mortars with FA were carried out according to the ASTM C618. The mechanical properties of FA were determined based on the SAI value obtained from the compressive strength test. For this purpose, mortar samples measuring 5 cm × 5 cm × 5 cm were prepared. The samples were cured for seven days by having been immersed in water. In the mechanical properties test, FA samples were used as a substitute for cement in mortars. Considering the mortar mixture (Table I), FA was utilized as a substitute for cement in the following proportions: 20%, 30%, and 40%, corresponding to sample codes I, II, and III, respectively. In addition, the effect of different water binder ratios (w/b) on the strength of mortar was investigated, with w/b set at 0.3, 0.4, and 0.5, corresponding to sample codes III, IV, and V, respectively. Furthermore, FABA samples were studied under two conditions: the first, (A), involved samples without grain size screening, while the second, (B), entailed samples with grain size screening that were passed through sieve number 200.

III. RESULTS AND DISCUSSION

A. Physical Properties

The physical properties of FABA samples are detailed in Table II. All FA samples passed the Fineness test, meeting the ASTM C618 standard, which requires less than 34% of the sample to be retained when wet-sieved on a 45 μm (no. 325) sieve. These results are further supported by the particle size distribution analysis, which exhibits that the average particle size of all FA samples is below 45 μm.

In contrast, the Fineness value for all BA samples is significantly higher than that proposed by the ASTM C618 standard, which is also confirmed by a visual observation of the samples (Figure 2), and the particle size distribution analysis, as anticipated because BA is a coarse and granular particle. The Fineness of the ash affects its pozzolanic reactivity, leading to better compressive strength and durability of concrete [36]. On the other hand, coarser ash may exhibit lower reactivity due to its smaller surface area for chemical reactions. Thus, based on the results of the Physical Properties test, it can be concluded that FA PLTU AA is more effective as a pozzolanic material. Chemical and mechanical tests will later validate these findings. Despite the fact that the particle size of BA does not meet the requirements to be used in Portland-Cement Concrete, BA employment in construction is still relatively high. The utilization of BA in Western countries reaches 70%-95%, whilst in the Netherlands and Denmark is almost 100% [37]. BA could be deployed in the construction industry for pavement construction and aggregate replacement in concrete [38].

TABLE I. THE MIXTURE PROPORTIONS OF MORTAR SAMPLES

No	Sample	w/b	Cement (gr)	Water (ml)	Sand (gr)	FA (gr)
1	MAI3	0.3	400	150	1375	100
2	MAII3	0.3	350	150	1375	150
3	MAIII3	0.3	300	150	1375	200
4	MBI3	0.3	400	150	1375	100
5	MBII3	0.3	350	150	1375	150
6	MBIII3	0.3	300	150	1375	200
7	MAI4	0.4	400	200	1375	100
8	MAII4	0.4	350	200	1375	150
9	MAIII4	0.4	300	200	1375	200
10	MBI4	0.4	400	200	1375	100
11	MBII4	0.4	350	200	1375	150
12	MBIII4	0.4	300	200	1375	200
13	MAI5	0.5	400	250	1375	100
14	MAII5	0.5	350	250	1375	150
15	MAIII5	0.5	300	250	1375	200
16	MBI5	0.5	400	250	1375	100
17	MBII5	0.5	350	250	1375	150
18	MBIII5	0.5	300	250	1375	200
19	Control	0.48	500	242	1375	-

TABLE II. PHYSICAL PROPERTIES OF FABA SAMPLES

No	Sample	Fineness (%)	Average Particle Size
1	FA-AA	6	6.4 μm
2	FA-PP	16	40.5 μm
3	FA-BK	10	40.5 μm
4	BA-AA	68	69.4 μm
5	BA-PP	96	78.5 μm
6	BA-BK	96	78,9 μm

B. Chemical Properties

1) Moisture Content and LoI Test

Several findings could emerge from the Moisture Content and LoI test of all FABA samples. A similar pattern to the Physical Properties test results could be observed in Moisture Content and LoI test findings. For PLTU AA samples, Moisture Content and LoI values are lower in FA samples. Conversely, for PLTU PP and BK samples, these values are higher in the FA samples. Moisture Content and LoI test results are shown in Table III. Concerning Moisture Content, almost all samples do not comply with the maximum value according to ASTM C618 (less than 3%), except for the FA-AA Sample. Moreover, the AS/NZS 3582.1 standard requires less than 0.5 Moisture Content, but the EN 450-1 standard does not explicitly address Moisture Content requirements [29]. On the contrary, in terms of the LoI test results, all samples follow the ASTM C618 requirements of less than 6%. The LoI of all samples even passes the more stringent AS/NZS 3582.1 standard, which requires LoI to be less than 3%. Thus, using FABA from PLTU PP and PLTU BK can be still considered. To minimize the negative effect of higher Moisture Content, FA from both PLTUs should be in a Saturated Surface-Dry (SSD) condition during mixing.

TABLE III. MOISTURE CONTENT AND LOI RESULTS OF FABA SAMPLES

No	Sample	Moisture Content (%)	LoI (%)
1	FA-AA	2.88	0.38
2	FA-PP	6.38	1.37
3	FA-BK	12.61	2.27
4	BA-AA	5.04	1.07
5	BA-PP	5.93	0.08
6	BA-BK	6.38	0.17

2) XRF Analysis

Regarding chemical composition, FABA from PLTU AA and PLTU BK demonstrate auspicious characteristics as sustainable construction materials, particularly as cement replacement materials. This is evidenced by the relatively high SiO_2 content in both samples, where the former has a significant effect on FA reactivity. The complete chemical composition of FABA samples from the XRF test can be observed in Table IV. In general, according to the ASTM standards, regarding the chemical composition, all samples can be potentially used in concrete mixtures.

TABLE IV. CHEMICAL COMPOSITION OF FABA SAMPLES

No	Sample	Chemical Composition (%)						
		SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	K_2O	MnO
1	FA-AA	24.9	7.5	52.57	8.79	-	0.65	0.67
2	FA-PP	17.8	6.1	36.8	30	4.5	0.74	0.41
3	FA-BK	27.2	14	37	12.5	-	0.93	0.72
4	BA-AA	41.4	6.5	40.46	7.81	-	0.48	0.56
5	BA-PP	29.2	7.8	25.3	33.2	1.1	0.27	0.31
6	BA-BK	39.2	12	27	15.7	-	0.79	0.65

According to the ASTM C618, FABA from PLTU AA and PLTU BK could be categorized as Class F FA due to the higher combined composition of SiO_2 + Al_2O_3 + Fe_2O_3, which is greater than 50% and a lower CaO content of less than 18%. In addition, although FABA from PLTU PP yields a high combined composition of SiO_2 + Al_2O_3 + Fe_2O_3, greater than 50%, the CaO content exceeds 18%. Thus, FABA PLTU PP is classified as Class C FA. As noted by many researchers, Class F FA generally has a better effect on concrete and mortar's compressive strength and durability than Class C FA [39-41]. Another thing that should be noted is the content of Potassium oxide (K_2O) and Sulfur trioxide (SO_3). K_2O and other alkali oxides could cause issues in concrete when present in higher amounts, such as an Alkali-Silica Reaction (ASR), and delay the hydration mechanism [30, 42, 43]. For this reason, the ASTM C311 standards limit the total alkali content to around 0.8% [31]. In addition, other studies proposed a limitation of alkali content to 2.3% and up to 3.8% [44]. Based on this perspective, it is essential to consider the alkali content of FA in the production of concrete made with potentially reactive aggregates to reduce ASRs. Moreover, based on the findings of [36], the K_2O content of almost all FABA Kalimantan is below the average K_2O content of the typical FA, which is 0.79%. As for SO_3, it typically reacts with other compounds in the cementitious matrix to form sulfates, such as calcium sulfoaluminate, $3CaO.Al_2O_3.3CaSO_4.32H_2O$, known as ettringite [45, 46]. Calcium sulfoaluminate adversely affects the bonding and cohesive characteristics of the hydration products [47]. Therefore, according to the ASTM C618, the SO_3 content in FA is limited to a maximum of 5% [29]. Based on the XRF results (Table IV), all FABA samples comply with the ASM C618 standard. According to the chemical composition results of the FABA samples taken from the XRF analysis, it is evident that Kalimantan FABA has significant potential as a sustainable construction material. The relatively high SiO_2 content and low alkali and SO_3 contents support this idea. Additionally, the XRF analysis will be further confirmed by the XRD analysis.

3) XRD Analysis

Figures 3-8 display the XRD analysis of all FABA samples. In general, these results are consistent with the findings from the XRF analysis. The intensity count of SiO_2 at 2Θ for BA samples is more than 800. In addition, as the SiO_2 content in the FA samples decreased compared to the BA samples, the SiO_2 intensity counts also reduced, ranging from approximately 200 to 300. The XRD analysis also confirmed the predominant elements detected by the XRF analysis, such as SiO_2, alumina (Al_2O_3) and iron (Fe_2O_3). As observed in Figures 3-8, XRD analysis could trace SiO_2, Al_2O_3, and Fe_2O_3 in all FABA samples.

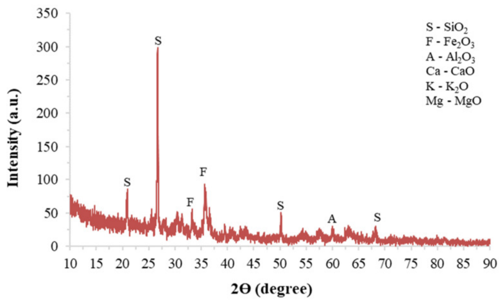

Fig. 3. XRD spectra of FA obtained from PLTU AA.

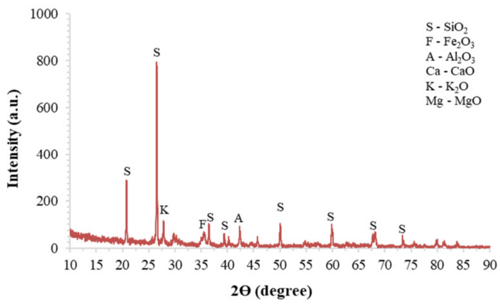

Fig. 4. XRD spectra of BA obtained from PLTU AA.

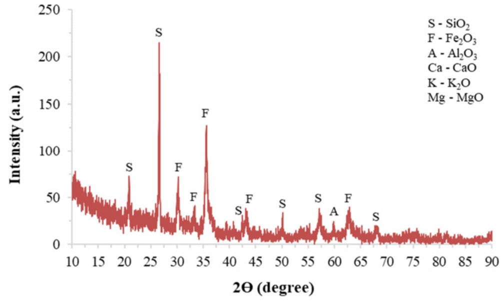

Fig. 5. XRD spectra of FAobtained from PLTU PP.

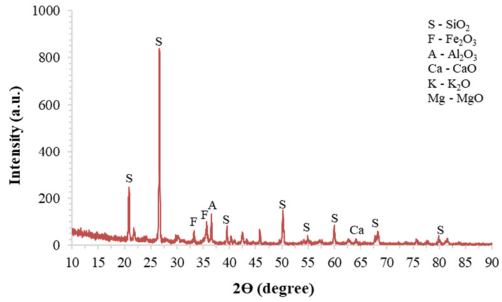

Fig. 6. XRD spectra of BA obtained from PLTU PP.

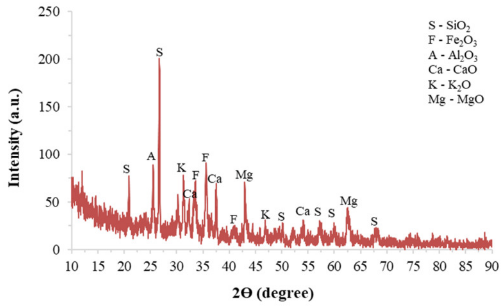

Fig. 7. XRD spectra of FA obtained from PLTU BK.

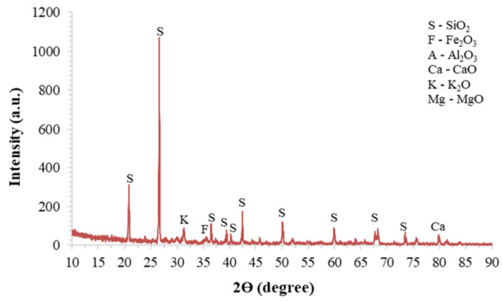

Fig. 8. XRD spectra of BA obtained from PLTU BK.

Furthermore, calcium oxide (CaO) can be observed in PLTU PP and BK samples. According to [48], higher elemental concentrations detected by XRF can be linked to specific crystalline phases detected by XRD. Moreover, SO_3 and MnO cannot be traced in all samples. This may be due to the low concentrations of these compounds, as revealed by the XRF analysis. Another possibility is that SO_3 and MnO are present within compounds formed from other materials. Regarding K_2O, it was detected only at 2Θ = 31.35 (47.75) in the XRD spectra of FA obtained from PLTU BK, as illustrated in Figure 7. These findings are consistent with previous studies [49-51].

C. Mechanical Properties

To evaluate the relationship between the physical and chemical properties of FA with its mechanical properties, this study also examines the SAI of FA from PLTU AA. Concerning the mortar tests using BA, they were not conducted in this study, since BA does not meet the ASTM C618 standards. Figure 9 presents the compressive strength and SAI value of the PLTU AA FA. According to the ASTM C618 standard, FA used in concrete must have a minimum SAI value of 75%. Therefore, only six samples fulfill the criteria to be utilized as pozzolanic materials in concrete, which are MBIII4 with an SAI of 105.44% (19.76 MPa), MBIII3 with an SAI of 101.97% (19.11 MPa), MAIII4 with an SAI of 94.24% (17.66 MPa), MAI5 with an SAI of 86.45% (16.2 MPa), MBI5 with an SAI of 85.91% (16.1 MPa), and MBII4 with an SAI of 81.96% (15.36).

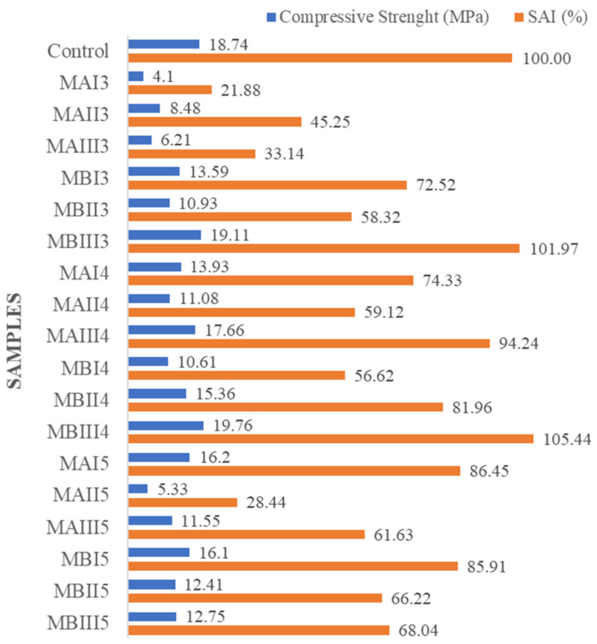

Fig. 9. Strength activity index of FA from PLTU AA.

On the basis of these results, there is a strong correlation between the physical properties of FA, i.e., Fineness, and its mechanical properties. This is particularly emphasized because, out of the six samples, only two mortar samples with unsieved FA, MAI5, and MAIII4, meet the criteria. In addition, it is observed that MBIII4 (sieved FA) exhibits a higher strength value compared to MAIII4 (unsieved FA). Different phenomena are only notable between the MBI5 and MAI5 samples, as well as between the MBI4 and MAI4 samples. However, it is important to note that the composition of the MBI4 and MAI4 samples does not meet the minimum SAI requirements, and the difference in strength between the MBI5 and MAI5 samples is insignificant. Furthermore, the results of this test also demonstrate the influence of the chemical characteristics on the potential use of FA as a pozzolanic material. The high levels of SiO_2, Al_2O_3, and Fe_2O_3 identified in the XRF and XRD analyses of FA from PLTU AA serve as significant indicators of its potential reactivity. Consequently, high SAI values, namely more than 75%, can be observed in six mortar samples.

IV. CONCLUSIONS

A series of tests were carried out to evaluate the physical, chemical, and mechanical characteristics of Kalimantan Fly Ash and Bottom Ash (FABA) to ensure its effectiveness and potential as a sustainable construction material. Based on all test results, several key findings have emerged:

- FA from all PLTUs has met the specifications for concrete use, according to the ASTM C618 standard, especially Fly Ash (FA) from PLTU Asam-Asam (AA). However, all Bottom Ash (BA) samples do not meet the minimum requirements needed.
- As for the chemical properties, all FA and BA meet the Loss on Ignition (LoI) values. On the contrary, in terms of Moisture Content, only FA from PLTU AA meets the requirements below 3%. However, EN 450-1 does not specify a maximum Moisture Content. Thus, using FABA from PLTU Pulang Pisau (PP) and PLTU Bengkayang (BK) can be still considered.
- X-ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analysis results have confirmed the potential of Kalimantan FABA as a sustainable material. This is based on a relatively high silica (SiO_2) content and chemical composition that meets ASTM C618 standards.
- The Strength Activity Index (SAI) test results validated the physical and chemical characteristics. Particle Fineness affects mortar strength, and the chemical composition indicates its potential as a Supplementary Cementitious Material (SCM).

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