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Valorisation of Faecal Sludge-Derived Bio-Briquette Ash as a Potential Supplementary Cementitious Material for Sustainable Construction

Deogratius A. Marenge[1] , Elke Knapen[2] , Shadrack.M.Sabai[3]

ABSTRACT

The increasing demand for sustainable construction materials and improved faecal sludge management has encouraged the exploration of waste-derived ashes as alternative supplementary cementitious materials. This study examined the use of Bio-Briquette Ash from faecal sludge as a supplementary cementitious material. Bio-briquettes with different binders (cassava peel and waste paper) and without binder were combusted in an open kitchen at 300–450°C, and the resulting ashes were analysed using X-ray fluorescence and X-ray diffraction techniques. The ash samples contained significant amounts of silica, alumina, and calcium oxide, with combined pozzolanic oxide contents ($SiO_2 + Al_2O_3 + Fe_2O_3$) ranging from approximately 67% to 70%, which is slightly below ASTM C618 requirement for pozzolanic materials. X-ray diffraction analysis showed that the ashes were dominated by crystalline quartz phases with limited amorphous content, indicating relatively low pozzolanic reactivity. In addition, the sulphate content exceeded the ASTM limits. The findings indicate that the bio-briquette ash produced under low-temperature combustion conditions does not meet the criteria for full compliance as a supplementary cementitious material. However, the ash shows potential for sustainable construction applications following further optimisation through controlled calcination, mechanical activation, or blended-cement systems. The mechanical and durability performances were not evaluated in this study.

Keywords: Circular economy; Pozzolanic materials; Thermal treatment; X-ray fluorescence; X-ray diffraction

INTRODUCTION

Cement production has a major environmental impact, particularly in rapidly growing cities such as Dar es Salaam in Tanzania, where urbanisation and waste generation are increasing (Andualem et al., 2019). The utilisation of waste materials as building materials has gained increasing attention as a strategy to reduce environmental impacts and improve resource efficiency (Sabai, 2013). Materials such as fly ash (FA), rice husk ash (RHA), and sugarcane bagasse ash (SCBA) are useful supplementary cementitious materials (SCMs) because they contain significant amounts of silica and exhibit strong pozzolanic activity (Charitha et al., 2021). Their performance depends on the firing temperature, which influences ash properties (Isemin et al., 2025). Many studies have examined the conversion of faecal sludge into bio-briquettes for energy(Chacha, 2024). However, research on the utilisation of the resulting bio-briquette ash (BBA) in construction materials remains limited. BBA may possess characteristics suitable for cementitious applications due to its chemical and mineralogical composition, which is influenced by combustion conditions,

[1] Deogratius Marenge is a member of academic staff at the UHasselt, Hasselt University, Martelarenlaan 42, 3500 Hasselt, Belgium. and the Department of Civil and Environmental Engineering, Ardhi University, Tanzania.
His email address is: deogratius.marenge@aru.ac.tz/deogratius.marenge@uhasselt.be

[2] Elke Knapen is a member of academic staff at UHasselt, Hasselt University, Martelarenlaan 42, 3500 Hasselt, Belgium.

[3] Shadrack M. Sabai is a member of academic staff at the Department of Civil and Environmental Engineering, Ardhi University, Tanzania

similar to other waste-derived ashes, such as fly ash, rice husk ash, and sugarcane bagasse ash, that have been extensively studied (Fapohunda et al., 2017).

Supplementary cementitious materials are effective primarily because they contain amorphous silica and alumina, which react with calcium hydroxide to form calcium silicate hydrate (C-S-H), the main compound responsible for concrete strength development (Chen et al., 2024). Industrial by-products, such as fly ash and blast-furnace slag, are commonly used as partial clinker replacements to improve mechanical performance and durability while reducing cement consumption (Parron-Rubio et al., 2019). Heat treatment conditions are particularly important for transforming raw materials into reactive, amorphous phases. Previous studies have shown that agricultural waste ashes generally achieve optimum pozzolanic performance when burned at temperatures between 500 and 700°C for approximately 90–120 minutes (Abu Talip et al., 2018). Temperatures outside this range may reduce pozzolanic reactivity due to incomplete transformation or excessive crystallisation.

Although previous studies have investigated the production and combustion behaviour of faecal sludge-derived bio-briquettes for energy applications (Mwamlima et al., 2023; Sanka et al., 2024), limited information is available regarding the chemical and mineralogical properties of the resulting ash and its suitability as a supplementary cementitious material. There is a lack of data concerning the oxide composition, crystalline phases, and pozzolanic potential of bio-briquette ash produced under decentralised low-temperature combustion conditions. This knowledge gap limits the assessment of whether such ash can contribute to sustainable construction materials and circular waste management strategies in the future. This study investigated the chemical and mineralogical composition of faecal sludge-derived bio-briquette ash produced with different binders. It evaluated its potential as a supplementary cementitious material by comparing it with the requirements of ASTM C618 (ASTM International, 2022) and conventional supplementary cementitious materials such as rice husk ash, sugarcane bagasse ash, and fly ash. If appropriately processed and validated, the use of BBA in construction materials could contribute to improved waste management, circular economy practices, reduced reliance on conventional raw materials, and lower carbon emissions in the construction sector.

MATERIALS AND METHODS

This study employed a combined literature-based comparative review and experimental investigation to evaluate the potential use of faecal sludge-derived bio-briquette ash (BBA) as a supplementary cementitious material. The literature review focused on the chemical composition and pozzolanic characteristics of commonly used supplementary cementitious materials, while the experimental work involved producing, combusting, and characterising bio-briquette ash derived from faecal sludge. The experimental methodology is presented in Figure 1.

Literature- Based Comparative Review

A literature review was conducted to collect information on the chemical composition, mineralogical characteristics, and combustion conditions of established supplementary cementitious materials, including rice husk ash (RHA) (Table 3), sugarcane bagasse ash (SCBA), and fly ash (FA). Previous studies were reviewed to identify the typical oxide compositions, silica contents, sulphate levels, and processing temperatures associated with pozzolanic performance. The collected data were used as reference values to compare the properties of the bio-briquette ash produced in this study with those of conventional supplementary cementitious

materials and with the ASTM C618 requirements.

Experimentation program

Faecal Sludge Collection and Pre-treatment

The faecal sludge used in this study was collected from the Mburahati Decentralised Wastewater Treatment Plant located in the Ubungo District of Dar es Salaam, Tanzania. The sludge represented a municipal waste stream containing organic matter, siliceous compounds, and minor inorganic constituents. The sludge collected after biological treatment at the Wastewater Treatment Plant was spread in thin layers and sun-dried for approximately 3–5 days to reduce its moisture content to a relatively stable dry mass. The dried sludge was subsequently carbonised in a sealed drum reactor under limited-oxygen conditions to convert the organic matter into a carbon-rich material suitable for briquette production. Carbonisation was conducted at temperatures ranging between 300 and 450°C for approximately 5–7 hours. This process reduced the volatile matter and stabilised the material prior to briquette formation.

Briquette Production

Three categories of bio-briquettes were produced using carbonised faecal sludge with different binder conditions: carbonised sludge with cassava peel powder binder, carbonised sludge with wastepaper pulp binder, and carbonised sludge without binder. Cassava peels were collected, sun-dried, ground into a powder, and mixed with water to form a slurry. Wastepaper was shredded and soaked in water for approximately 48 hours to produce a pulp slurry. The briquette mix proportions were prepared on a dry weight basis, as shown in Table 1.

Table 1. Briquette Mix Proportions

Briquette Type	Carbonised Sludge (%)	Binder Type	Binder Content (%)
Cassava-binder briquette	80	Cassava peel powder	20
Paper-binder briquette	80	Wastepaper pulp	20
Binder-free briquette	100	None	0

The constituent materials were manually mixed until a homogeneous consistency was obtained. Water was gradually added during mixing to improve workability. The mixtures were moulded into cylindrical briquettes of approximately 50 mm diameter and 50 mm height using manual compaction with an estimated equivalent pressure of approximately 1–2 MPa. The formed briquettes were air-dried for 5–7 days under ambient conditions prior to combustion.

Ash Generation

The dried briquettes were combusted in a traditional open-air stove to generate bio-briquette ash (BBA). Combustion was conducted under relatively uncontrolled atmospheric conditions at temperatures ranging from 300 to 450°C, with a residence time of approximately 1–2 hours. The low combustion temperature reflects decentralised, household-scale thermal processing conditions commonly used in developing regions (Reinmöller et al., 2023). These combustion conditions strongly influence the mineralogical structure, crystallinity, and pozzolanic reactivity of the resulting ash.

After combustion, the ash samples were naturally cooled under ambient conditions. Partially burnt residues and oversized particles were removed manually. The ash was subsequently sieved through a 75 μm mesh sieve to obtain a relatively uniform particle size before laboratory analysis. The processed ash samples were stored in sealed containers to minimise moisture absorption and contamination. To improve the experimental reliability, all ash samples

were prepared and analysed in triplicate (n = 3), and the average values were reported.

Experimental Setup

The experimental setup consisted of sludge-drying trays, a sealed drum reactor for carbonisation, manual briquette moulds, and an open traditional stove for generating ash. Carbonisation was conducted under limited oxygen conditions, whereas combustion occurred under open-air conditions. The overall experimental workflow included sludge drying, carbonisation, briquette production, combustion, ash collection and laboratory characterisation

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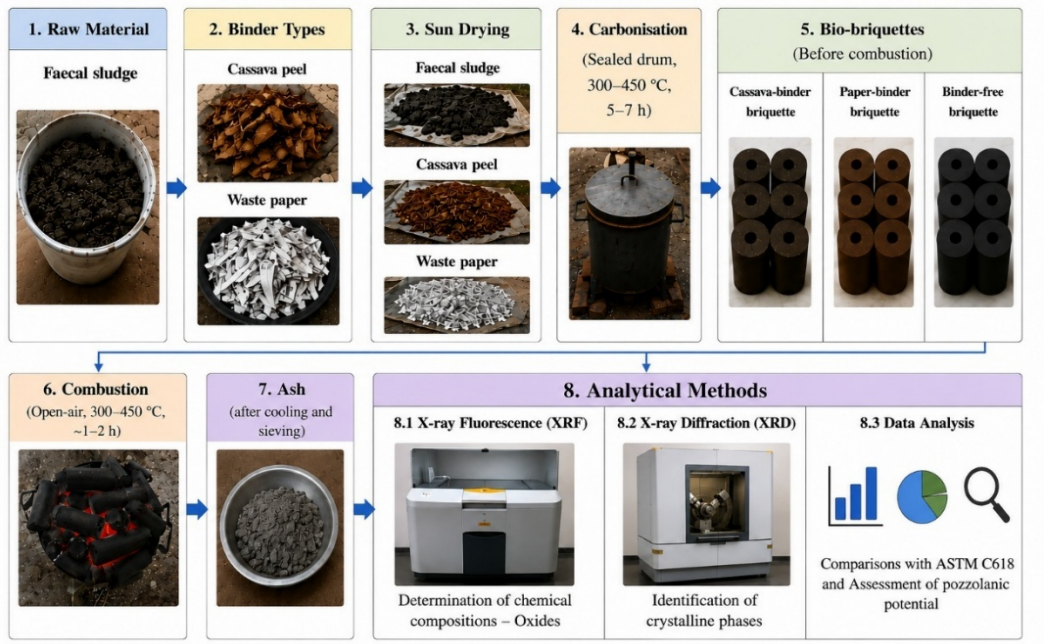


Figure 1: Experimental setup of bio briquette production, combustion and analysis

Chemical Characterisation Using X-ray Fluorescence (XRF)

The chemical composition of the bio-briquette ash samples was determined using X-ray fluorescence (XRF) spectrometry at the Twiga Cement Laboratory using a Bruker AXS S8 TIGER spectrometer. Approximately 2 g of each ash sample was compressed under a pressure of 200 kN to produce circular pellets with a diameter of 34 mm. The pellets were placed in aluminium sample holders and analysed to determine the oxide composition of the ash samples. XRF analysis was selected because it enables the accurate quantification of major oxides relevant to pozzolanic assessment, including SiO_2, Al_2O_3, Fe_2O_3, CaO, and SO_3.

Mineralogical Characterisation Using X-ray Diffraction (XRD)

Mineralogical analysis of the ash samples was performed using X-ray diffraction (XRD) spectrometry with a Bruker D2 Phaser XRD machine at the Twiga Cement Laboratory. For each sample, 9 g of ash was mixed with 1 g of wax micropowder and ground thoroughly to achieve homogeneity. The mixture was compressed at 70 kN to form pellets suitable for XRD analysis. The XRD instrument operated at 30 kV and 10 mA using Cu-Kα radiation with a wavelength of 1.540598 Å. Scanning was conducted within the 2θ range of 4.881°–64.857°. Mineral phase identification was performed using Match software. XRD analysis was used to determine the crystalline and amorphous phases present in the ash samples, which are important indicators of pozzolanic reactivity of the ash.

Pozzolanic Assessment

The pozzolanic potential of the produced bio-briquette ash was evaluated in accordance with

the ASTM C618 requirements for supplementary cementitious materials. The combined oxide content of SiO_2, Al_2O_3, and Fe_2O_3 was calculated and compared with the ASTM minimum requirement of 70% for Class N and Class F pozzolanic materials. The sulphate (SO_3) content of the ash samples was also evaluated against the ASTM limits. However, the present study assessed only the chemical compliance aspect of ASTM C618. Other important parameters required for full pozzolanic qualification, including loss on ignition (LOI), fineness, strength activity index, and durability performance, were not investigated in this study.

3.0 RESULTS AND DISCUSSION

Chemical and Mineral Composition of Bio-Briquette Ash and Its Pozzolanic Potential

Chemical Composition of Bio-Briquette Ash

The chemical compositions of the bio-briquette ash samples produced using different binders were determined using X-ray fluorescence (XRF) analysis, as shown in Figure 2. The major oxides identified in all samples were silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and sulphur trioxide (SO_3), which are commonly used to evaluate the suitability of supplementary cementitious materials. The ash produced using the cassava peel binder contained approximately 51.2% SiO_2, 14.4% Al_2O_3, and 2.14% Fe_2O_3, resulting in a combined pozzolanic oxide content (SiO_2 + Al_2O_3 + Fe_2O_3) of approximately 67.7%. Similarly, the paper-binder and binder-free ashes recorded combined oxide contents of approximately 69.3% and 69.6%, respectively, which are comparable. Although these values are close to the minimum ASTM C618 requirement of 70% for Class N and Class F pozzolanic materials, none of the samples fully satisfied this standard.

The relatively high silica and alumina contents observed in the ash samples indicate the presence of compounds capable of participating in pozzolanic reactions. Silica and alumina are important because they react with calcium hydroxide in cementitious systems to form secondary calcium silicate hydrate (C-S-H) gels, which contribute to strength development and matrix densification. However, the slightly lower combined oxide content suggests that the ash produced possesses only moderate pozzolanic potential in its current state. A notable observation was the relatively high SO_3 content across all samples, ranging from approximately 6.8% to 7.1%, which exceeded the ASTM C618 allowable limit of 4–5%. The elevated sulphate content may be associated with incomplete combustion and residual inorganic compounds resulting from the relatively low-temperature combustion conditions used in this study. High sulphate levels may negatively affect long-term durability by increasing the risk of expansion, sulphate attack, and delayed ettringite formation in cementitious systems. This suggests that further optimisation of the combustion process is required before the ash can be safely used in cement-based materials.

The ash samples also contained relatively high CaO content, ranging from approximately 10.7% to 11.3%. The presence of CaO may contribute to limited hydraulic or self-cementing behaviour, particularly when combined with reactive silica phases. This indicates that the ash may exhibit both partial cementitious and pozzolanic characteristics, although its overall reactivity is constrained by the production conditions. The relatively small variation in the oxide composition among the three ash types indicates that the binder type had a limited influence on the final chemical composition of the ash. This suggests that the mineral composition of the original faecal sludge feedstock and the combustion conditions had a greater influence on ash characteristics than the organic binders used during briquette production.

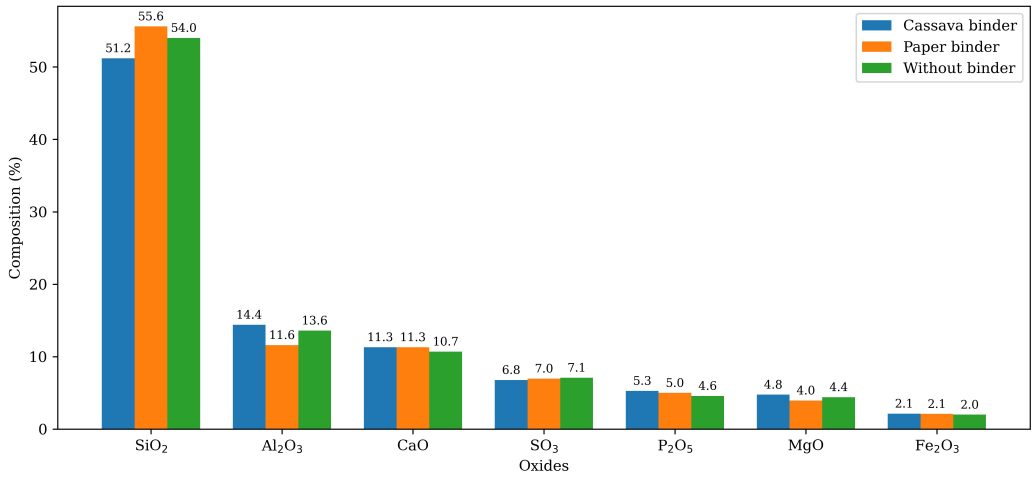


Figure 2. Major oxide composition of bio-briquette ash samples produced using different binders (oxide composition expressed in %)

Mineralogical Composition of Bio-Briquette Ash

The mineralogical compositions of the produced bio-briquette ash samples were analysed using X-ray diffraction (XRD), as shown in Figure 3. The XRD diffractograms revealed that the ash samples were dominated by crystalline phases, with a major diffraction peak occurring at approximately 26.7° 2θ. This peak primarily corresponds to quartz, indicating that crystalline silica is the dominant mineral phase in the ash. Additional secondary peaks were observed at approximately 20.9°, 50.2°, and 60.0° 2θ, further confirming the presence of crystalline silica minerals. In the paper-binder and binder-free ash samples, an additional peak near 29.5° 2θ suggested the presence of calcite phases, which were likely associated with calcium-rich inorganic constituents in the sludge. Compared with the cassava-binder ash, the paper-binder ash exhibited slightly more pronounced secondary crystalline reflections, indicating a relatively higher degree of mineral ordering in the latter. However, all the ash samples exhibited similar mineralogical behaviour, characterised by dominant crystalline phases. An important observation from the diffractograms is the limited presence of a broad amorphous hump within the range commonly associated with amorphous silica phases (approximately 20–35° 2θ). The absence of a significant amorphous phase indicates the relatively low pozzolanic reactivity of the produced ash. Highly reactive supplementary cementitious materials typically contain substantial amounts of amorphous silica that readily reacts with calcium hydroxide during cement hydration.

The predominance of crystalline quartz in the ash is mainly attributed to the relatively low combustion temperatures (300–450°C) used during open-air combustion. Previous studies have shown that controlled calcination at temperatures between approximately 500 and 700°C promotes the formation of amorphous silica phases with higher pozzolanic activity. In contrast, insufficient thermal treatment may result in incomplete mineral transformation and the retention of crystalline phases with limited reactivity. These findings indicate that although the produced ash contains potentially useful oxide compositions, its mineralogical structure limits its effectiveness as a highly reactive pozzolanic material. Therefore, further optimisation of the combustion conditions, controlled calcination, or mechanical activation may be required to improve its reactivity and suitability for cementitious applications.

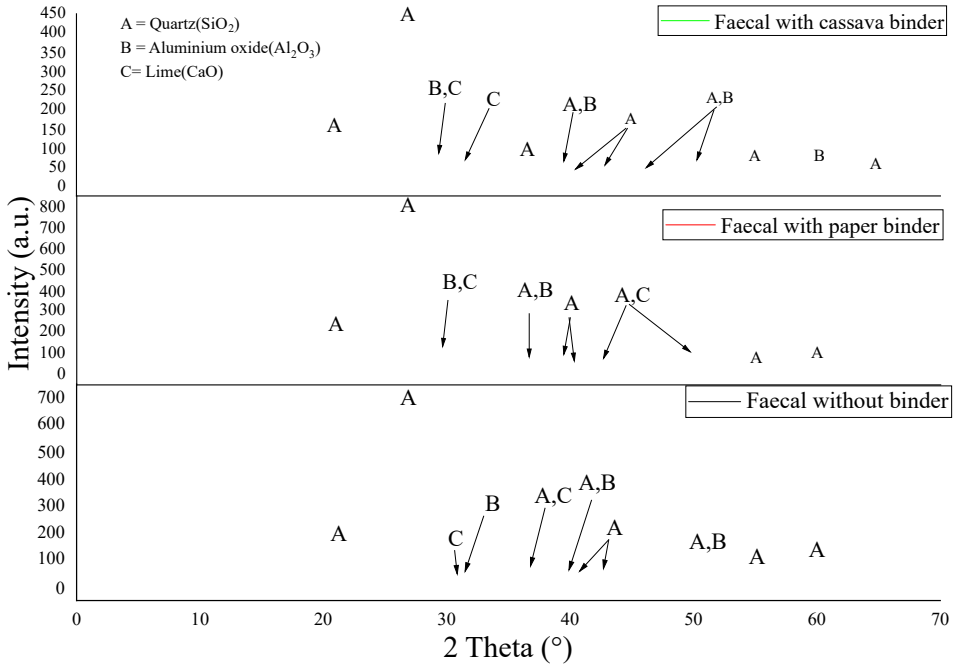


Figure 3. XRD diffractograms of bio-briquette ash samples produced using cassava binder, paper binder, and without a binder

Comparison with Conventional Supplementary Cementitious Materials

The chemical composition of the bio-briquette ash (BBA) was compared with that of commonly used supplementary cementitious materials, including rice husk ash (RHA), sugarcane bagasse ash (SCBA), and fly ash (FA), as presented in Table 2 and Table 3. The comparison revealed significant differences in the oxide composition, sulphate content, and expected pozzolanic behaviour.

Table 2. Comparison of BBA samples with ASTM C618, Conventional SCMs (RHA, SCBA, and FA)

Parameter	ASTM C618 Requirement	Cassava Binder-BBA	Paper Binder-BBA	Binder-Free BBA	RHA (Literature Range)	SCBA (Literature Range)	FA (Literature Range)
SiO_2 (%)	—	51.2	55.6	54.0	73.6–94.84	64.7–68.5	20–60
Al_2O_3 (%)	—	14.4	11.6	13.6	0.07–6.19	4.2–5.3	5–35
CaO (%)	—	11.3	11.3	10.7	0.39–3.30	5.8–7.2	1–12
SO_3 (%)	≤4–5	6.8	7.0	7.1	0.01–1.21	0.1–0.2	0–4
P_2O_5 (%)	—	5.3	5.0	4.6	—	—	—
MgO (%)	—	4.8	4.0	4.4	0.10–1.45	2.1–2.8	0–5
Fe_2O_3 (%)	—	2.1	2.1	2.0	0.10–3.65	2.9–3.8	7–40
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	≥70	67.7	69.3	69.6	77.5–95.8 ✓	73.5–77.0 ✓	>70 ✓
Burning Temperature (°C)	—	<500	<500	<500	500–750	500–800	800–1,300
Pozzolanic Suitability	Required	Marginal	Marginal	Marginal–Moderate	High	Moderate–High	Moderate–High

Rice husk ash generally contains very high silica content, ranging from approximately 74% to 95%, which contributes to its strong pozzolanic reactivity. Sugarcane bagasse ash also contains relatively high silica levels, typically between 65% and 69%, along with moderate alumina and iron oxide contents, which enhance cementitious performance. Fly ash compositions vary considerably depending on the coal source

and combustion conditions, with silica contents ranging from approximately 20% to 60%. Compared to these conventional materials, BBA has a moderate silica content (approximately 51–56%) and a relatively high alumina content (approximately 12–14%). Although its combined oxide content approaches the ASTM requirements, it remains slightly below the minimum threshold required for full pozzolanic classification. This indicates that BBA may exhibit moderate pozzolanic activity but requires further improvement to function as a conventional supplementary cementitious material (SCM).

One of the major differences between BBA and conventional SCMs is the relatively high SO_3 content observed in BBA (approximately 7%), whereas RHA, SCBA, and most fly ashes generally contain sulphate levels below the ASTM limits. The elevated sulphate content in BBA is likely attributable to the characteristics of the faecal sludge feedstock and the low-temperature, uncontrolled combustion process used in this study. Excessive sulphate levels may negatively influence the dimensional stability and long-term durability of cementitious systems. The mineralogical behaviour of BBA also differs from that of highly reactive SCMs because of the predominance of crystalline silica phases and limited development of amorphous phases. Conventional RHA and SCBA are usually produced under carefully controlled calcination temperatures, which promote amorphous silica formation and higher reactivity. In contrast, the decentralised combustion conditions used in this study promoted incomplete mineral transformation and reduced the pozzolanic activity. Despite these limitations, the relatively high CaO content in BBA suggests the potential for limited hydraulic behaviour, which may contribute to strength development when blended with cement or other highly reactive supplementary materials. Therefore, BBA may still have potential for use in blended cementitious systems after appropriate thermal treatment, grinding, and chemical activation.

Assessment of Pozzolanic Properties Based on ASTM C618

The suitability of bio-briquette ash as a supplementary cementitious material was assessed based on the chemical requirements specified in ASTM C618. According to the standard, the combined oxide content of SiO_2, Al_2O_3, and Fe_2O_3 should be at least 70% for Class N and Class F pozzolanic materials. In addition, the sulphate content (SO_3) must remain within acceptable limits, generally not exceeding 4–5%. The XRF results showed that the combined oxide contents of the produced ash samples ranged from approximately 67.7% to 69.6%, which is slightly below the ASTM requirement. Furthermore, the measured SO_3 content exceeded the allowable ASTM limit. Based on these results, the bio-briquette ash produced cannot currently be classified as a fully compliant pozzolanic material according to ASTM C618. However, the ASTM C618 classification is not based solely on chemical composition. Other important parameters, including loss on ignition (LOI), fineness, moisture content, strength activity index, and durability performance, are also required to fully evaluate supplementary cementitious materials. However, these parameters were not investigated in the present study. Therefore, this study assessed only the chemical compliance aspect of ASTM C618 and did not confirm the full performance compliance of the produced ash. The findings indicate that the ash possesses moderate pozzolanic potential but requires additional processing and performance evaluation before practical application in cementitious materials. The predominance of crystalline silica observed in the XRD analysis further supports the conclusion that the ash produced is relatively unreactive under the current processing conditions. Improved thermal treatment through controlled calcination at higher temperatures, mechanical grinding to increase fineness, or blending with highly reactive pozzolanic materials may enhance the ash's performance and improve its suitability for sustainable construction applications.

SCM Type	Author(s)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	Burning Temperature (°C)
BBA	Cassava binder (This study)	51.2	14.4	2.1	11.3	4.8	6.8	—	—	<500
	Paper binder (This study)	55.6	11.6	2.1	11.3	4.0	7.0	—	—	<500
	Binder-free (This study)	54.0	13.6	2.0	10.7	4.4	7.1	—	—	<500
RHA	Swaminathan and Ravi (2016)	87.2	0.15	0.16	0.55	0.35	0.24	—	—	500–700
	Mahmud et al. (2016)	85.76	0.25	1.15	0.74	0.81	0.31	—	—	600–700
	Foong et al. (2015)	93.46	0.58	0.52	1.03	0.51	—	1.82	0.08	500
	Bansal and Antil (2015)	87.2	0.15	0.16	0.55	0.35	0.24	—	—	500–700
	Le et al. (2014)	86.81	0.50	0.87	1.04	0.85	—	3.16	0.69	600
	Sivakumar and Mahendran (2014)	87.65	0.22	0.24	0.39	0.28	0.15	2.98	1.10	550–650
	Kumar and Venugopal (2013)	93.8	0.74	0.30	0.89	0.32	0.28	3.37	0.12	500–700
	Marthong (2012)	75.0	1.29	0.78	3.30	0.22	0.20	1.50	0.40	<500
	De Souza et al. (2011)	73.6	0.07	0.26	0.76	0.27	—	1.17	0.09	<500
	Memon et al. (2011)	77.19	6.19	3.65	2.88	1.45	—	1.81	0.00	600–700
	Shukla et al. (2011)	87.2	0.15	0.16	0.55	0.35	0.24	—	—	500–700
	Madandoust et al. (2011)	90.9	0.83	0.60	0.80	0.56	—	—	—	550–750
	Raman et al. (2011)	89.87	0.14	0.94	0.49	—	—	2.16	0.25	500–600
	Hwang et al. (2011)	91.0	0.35	0.41	—	0.81	1.21	3.21	0.08	600–700
	Zerbino et al. (2011)	94.84	0.39	0.54	1.32	0.40	0.01	1.45	0.11	550–750
	Habeeb and Mahmud (2010)	88.32	0.46	0.67	0.67	0.44	—	2.91	—	≤690
SCBA	Chindaprasirt et al. (2008)	93.2	0.40	0.10	1.10	0.10	0.90	1.30	0.10	550–750
	Cordeiro et al. (2009)	66.2	4.5	3.2	6.1	2.4	0.1	9.3	0.2	500–700
	Frías et al. (2011)	65.3	5.1	3.5	7.2	2.8	0.2	8.7	0.3	600–800
	Chusilp et al. (2009)	68.5	4.2	2.9	5.8	2.1	0.1	8.5	0.3	600–700
	Martirena et al. (2006)	64.7	5.3	3.8	6.5	2.5	0.2	9.0	0.4	500–600
	James et al. (2012)	66.8	4.6	3.3	6.2	2.4	0.1	9.2	0.2	500–700
	Nuntachai et al. (2009)	65.0	5.2	3.6	6.6	2.5	0.2	8.9	0.3	600–750
FA	Vassilev et al. (2010)	20–60	5–35	10–40	1–12	0–5	0–4	0–3	0–4	800–1,200
	Strzałkowska (2020)	45.3	23.8	10.2	7.1	3.2	1.4	2.3	0.7	950–1,100
	Kato et al. (2022)	52.4	28.3	8.7	3.6	1.2	0.5	2.4	0.9	1,000–1,200
	Kundu (2022)	54.7	24.1	9.8	5.3	2.6	1.2	1.7	0.6	900–1,100
	Adamiec et al. (2011)	50.1	26.2	11.3	5.8	2.1	0.8	1.5	0.5	850–1,100
	Zierold and Odoh (2020)	48.2	25.7	9.5	6.2	2.3	1.0	1.9	0.6	800–1,200
	Ha et al. (2016)	47.8	27.3	10.4	6.9	2.8	1.3	2.0	0.8	1,000–1,300
	Zhang et al. (2019)	49.6	26.1	9.9	5.4	2.4	0.9	1.8	0.7	900–1,100
	McCarthy et al. (1990)	46.0	28.0	11.0	7.0	3.0	1.5	2.2	0.6	850–1,200
	Jeyageetha et al. (2019)	55.0	26.0	7.0	9.0	2.0	1.0	1.8	0.5	950–1,200

Table 3. Presentations of Different BBA Samples from experiments and Conventional SCMs (RHA, SCBA, and FA) from the literature

LIMITATIONS OF THE STUDY

This study had several limitations. The bio-briquette ash (BBA) was produced under low-temperature, uncontrolled, open-air combustion (300–450°C), which favoured the formation of crystalline phases and a high sulphate content, thereby limiting amorphous silica formation, which is crucial for pozzolanic reactivity. These conditions differ from those used for the controlled calcination of conventional cementitious materials. This study primarily focused on the chemical and mineralogical characterisation using XRF and XRD. Other parameters, such as loss on ignition, fineness, moisture, and strength activity index, as per ASTM C618, were outside the scope of this study; therefore, only chemical compliance was assessed. This study focused solely on characterising ashes, without conducting mechanical or durability performance tests. The chemical compositions of agro-based and industrial ashes were obtained from previous studies rather than through laboratory experiments. Despite these limitations, this study offers valuable initial insights into BBA's chemical and mineralogical features of BBA, laying the groundwork for future research on controlled processing, performance testing, and sustainable use in construction.

CONCLUSION

This study investigated the chemical and mineralogical characteristics of faecal sludge-derived bio-briquette ash (BBA) produced using cassava peel binder, wastepaper binder, and without binder, and evaluated its potential as a supplementary cementitious material (SCM). The results showed that all the ash samples contained significant amounts of silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which are important constituents associated with pozzolanic and cementitious behaviour. However, the combined oxide contents ($SiO_2 + Al_2O_3 + Fe_2O_3$) of the produced ashes were slightly below the minimum ASTM C618 requirement of 70% for Class N and Class F pozzolanic materials. X-ray diffraction analysis revealed that the ash samples were dominated by crystalline phases, particularly quartz, with limited evidence of amorphous silica formation. The predominance of crystalline mineral phases is mainly attributed to the relatively low and uncontrolled combustion temperatures used during the ash production. In addition, the relatively high sulphate (SO_3) content observed in all ash samples exceeded the ASTM allowable limits, indicating the need for improved thermal processing conditions before practical utilisation in cementitious systems.

The findings indicate that the bio-briquette ash produced under the investigated conditions cannot be classified as a fully compliant supplementary cementitious material according to ASTM C618. Nevertheless, the ash exhibited moderate pozzolanic characteristics and partial cementitious potential due to its oxide composition and calcium content. The relatively small variation in chemical composition among the different binder types further suggests that combustion conditions and sludge composition had a greater influence on ash properties than the binder materials used in briquette production. Compared with conventional supplementary cementitious materials such as rice husk ash, sugarcane bagasse ash, and fly ash, BBA has a lower silica content, higher sulphate levels, and lower expected reactivity because of the predominance of crystalline phases. These differences highlight the importance of controlled calcination and material processing in improving the ash reactivity and pozzolanic performance. Overall, the study demonstrates that ash from faecal

sludge-derived bio-briquettes has potential as a supplementary cementitious material, provided it undergoes further optimisation and performance validation. Future research should focus on controlled calcination at higher temperatures, mechanical grinding, chemical activation, blended cement formulations, and the evaluation of engineering performance, including strength development and durability assessment, to determine the practical applicability of BBA in sustainable construction materials.

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ORCID ID: Deogratius Amedeus Marenge: https://orcid.org/0009-0008-8493-878X

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