PROPERTIES OF GROUND COAL BOTTOM ASH AND BLAST FURNACE SLAG TERNARY BLENDED CEMENT, MORTAR AND CONCRETE

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by

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ANOVA	Analysis of variance
BET	Bruneur Emmer Teller analysis
BS EN	British Standard European Norm
C-A-H	Calcium aluminate hydrate
CBA/GCBA	Coal bottom ash/Ground coal bottom ash
CCR	Calcium carbide residue
CH	Calcium hydroxide
CO_2	Carbon dioxide
CPS	Calcined paper sludge
C-S-H	Calcium silicate hydrate
DCW	Demolition ceramic waste
EDX	Energy-dispersive X-ray spectroscopy
FA	Fly ash
GGBS	Ground granulated blast furnace slag
GHG	Greenhouse gases
HPEG	Methylallyl polyoxyethylene ether
ICPMS	Inductively Coupled Plasma Mass Spectrometry
IEA	International Energy Agency
LOI	Loss on ignition
LPA	Laser particle analysis
LSF	Lime saturation factor
MK	Metakaolin
MS EN	Malaysian Standard European Norm
OPC	Ordinary Portland cement
PAI	Pozzolanic activity index
PCE	Polycarboxylate ether
RHA	Rice husk ash
RPM	Revolution per minute
S/B ratio	Sand-to-binder ratio
SAI	Slag activity index
SCM	Supplementary cementitious material
SEM	Scanning electron microscope
SF	Silica fume
SG	Specific gravity
SSA	Specific surface area
UPV	Ultrasonic pulse velocity
W/B ratio	Water-to-binder ratio
WGS	Water glass solution

SIFAT-SIFAT ABU ARANG BAWAH DAN SANGA RELAU BAGAS TERKISAR SIMEN MORTAR DAN KONKRIT CAMPURAN TERNARI

ABSTRAK

Abu arang bawah (CBA) boleh dikelaskan sebagai bahan pozzolanic kelas F mengikut ASTM C618 dan digunakan sebagai pengikat bahan dalam konkrit. Dalam kajian terdahulu, CBA telah dikisar dengan menggunakan pengisar bebola makmal untuk digunakan sebagai bahan penganti simen. Namun, pengoptimuman parameter pengisaran tidak dikaji untuk mencapai kadar penghasilan abu arang bawah dikisar (GCBA) yang optimum dan kualiti. Oleh itu, CBA dikisar pada pelbagai tempoh pengisaran, halaju sudut dan nisbah CBA kepada media pengisaran untuk menentukan optimum parameter pengisaran. Seterusnya, sifat fizikal dan kimia simen campuran yang mengandungi GCBA dan sanga relau bagas terkisar (GGBS) sehingga 25% telah dikaji untuk menentukan nisbah gabungan optimum GCBA dan GGBS. Akhir sekali, sifat mekanikal dan ketahanan konkrit campuran ternari mengandungi 20 sehingga 80% GGBS dan GCBA dalam nisbah 9:1 dan 7:3 telah dikaji. Hasil ujian menunjukkan optimum tempoh pengisaran, halaju sudut dan nisbah CBA kepada media pengisaran merupakan 5 jam, 70 putaran seminit (RPM) dan 1.5:10. Selain itu, nisbah gabungan optimum GGBS dan GCBA yang diperolehi merupakan 35% GGBS dan 15% GCBA (GGBS: GCBA = 7:3). Konkrit campuran mengandungi 20 sehingga 60% GGBS dan GCBA dengan GGBS: GCBA pada 9:1 dan 7:3 telah mencapai sifat mekanikal dan pertahanan yang setanding atau lebih baik daripada konkrit campuran kawalan. Di samping itu, kebolehtelapan udara intrinsik, jumlah keliangan dan penyerapan air di konkrit campuran mengandungi 20 sehingga 60% GGBS dan GCBA pada kedua-dua nisbah adalah setanding atau lebih rendah daripada konkrit kawalan.

PROPERTIES OF GROUND COAL BOTTOM ASH AND BLAST FURNACE SLAG TERNARY BLENDED CEMENT, MORTAR AND CONCRETE

ABSTRACT

The coal bottom ash (CBA) can be classified as Class F pozzolanic material according to ASTM C618 and used as a constituent binder in concrete. In the prior research, the CBA was pulverized in a laboratory ball mill to be used as supplementary cementitious material (SCM). However, the optimum milling parameters was not investigated to achieve the optimum output rate and quality of ground coal bottom ash (GCBA). Therefore, CBA was subjected to pulverization at various retention time, angular velocity of mill and CBA to instantaneous media ratio to determine the optimum milling parameters of the GCBA. Subsequently, the physical and chemical properties of the blended cement containing up to 50% of GCBA and ground granulated blast furnace slag (GGBS) was evaluated to determine the optimum combination ratio of the GCBA and GGBS. Lastly, the mechanical and durability properties of the ternary blended concrete containing 20 to 80% GGBS and GCBA at GGBS: GCBA of 9:1 and 7:3 was evaluated. The result demonstrated that optimum retention time, angular velocity of mill and CBA to instantaneous media ratio were 5 hours, 70 revolution per minute (RPM) and 1.5:10, respectively. On the other hand, the optimum combination ratio of GGBS and GCBA obtained was 35% GGBS and 15% GCBA (GGBS: GCBA = 7:3). At GGBS: GCBA of 9:1 and 7:3, the blended concrete with 20 to 60% of GGBS and GCBA achieved comparable or enhanced mechanical and durability performance compared to control concrete. The intrinsic air permeability, total porosity and water absorption of blended concrete with 20 to 60% of GGBS and GCBA at both ratios were similar or lower than the control concrete.

CHAPTER 1

INTRODUCTION

1.1 Background

According to Andrew (2018), the growth of global cement production has risen more than thirty-fold and four-fold since 1950 and 1990, respectively. International Energy Agency (IEA) revealed that the worldwide cement production in 2018 was 4.1 gigatons. Meanwhile, cement production in Malaysia increased from 17.56 million metric tons to 19.48 million metric tons from 2018 to 2020 (Statista Research Department, 2021). The process of manufacturing clinker, which is the main constituent of Ordinary Portland Cement (OPC) and combustion of fossil fuels in cement production, released a significant amount of carbon dioxide (CO_2) to the atmosphere (Andrew, 2018). The CO_2 intensity of cement manufacturing grew by 0.5% from 2014 to 2018. An annual reduction of 0.8% is required by 2030 (IEA, 2018). A review done by Benhelal *et al.* (2012) reported that around 0.9 tons of CO_2 discharged into the atmosphere for every ton of cement produced. Hence, the total carbon dioxide emissions from the cement industry were 3.7 gigatonnes in 2018.

Concrete is the most widely used material in construction applications. However, the concrete incorporating pure OPC tends to deteriorate faster under exposure to harsh environment (In *et al.*, 2016). Therefore, it is important to ensure the ability of the concrete to protect the reinforcement from corrosion. It was reported that the corrosion resistance and strength performance of the concrete was enhanced by incorporation of mineral admixture such as fly ash in concrete (Maslehuddin *et al.*, 1989). A durable concrete will maintain in its original form when it is exposed to aggressive environment. It was observed that the concrete containing ground coal bottom ash had better resistance to chloride ingress (Mangi *et al.*, 2018). Meanwhile, the use of alccofine and coal bottom ash as cement replacement material also led to 15% strength increment compared to the full OPC concrete (Reddy, 2016).

The supplementary cementitious material (SCM) such as rice husk ash (RHA), ground granulated blast furnace slag (GGBS) and fly ash (FA) were introduced for cement replacement in concrete. The expansions caused by alkali silica reaction (ASR) can be mitigated by utilization of SCM in concrete. The aluminum provided by the SCM will reduces the solubility of silica in alkaline solutions, preventing ASR expansion (Mangi *et al.*, 2018). The use of binary and ternary blended concrete are widely implemented in the current construction industry to reduce the usage of OPC and thus decrease the emission of CO_2.

Ground granulated blast furnace slag (GGBS) is a by-product generated from the manufacture of iron and commonly used as a mineral admixture in concrete. The mixtures of iron ore, limestone and coke are fed into the blast furnace and burn up to 2000°C. After transformation into iron, the ore sinks to the bottom of blast furnace, while other components float on top of the iron as slag. The blast furnace slag is then subject to water quenching followed by drying and pulverizing to a finer powdered form. The emission of greenhouse gases (GHG) from the manufacturing of GGBS is up to 80% lower than the emission of GHG from the production of OPC (Pradeep U *et al.*, 2016).

Moreover, it was reported that the slow reaction rate of GGBS with water was due to its latent hydraulic properties. A deceleration in the reaction between water and GGBS was noticed after a thin film of silica-rich gel was generated on GGBS particles' surface. Hence, alkali activated GGBS was produced by incorporation of strong alkali in the forms of hydroxide to enhance the reaction rate of GGBS. The main crystalline phase formed in the GGBS are melilite and merwinite ($Ca_3Mg(SiO_4)_2$), where melilite is a solid solution of akermanite ($Ca_2MgSi_2O_7$) and gehlenite ($Ca_2Al(AlSi)O_7$). As a result, the hydration of GGBS will form tricalcium-aluminate-hydrate ($Ca_3Al_2O_6$) and tricalcium-disilicate-hydrate (Ca_3O_5Si) as the main hydration products (Cheah *et al.*, 2021). Although GGBS blended concrete had lower early strength than full OPC concrete due to the slower formation of C-S-H gel. However, GGBS can improve the binding of calcium hydroxide (CH) compounds and result in the formation of C-S-H gel in concrete, increasing the concrete strength at a later age (Suda and Srinivasa Rao, 2020).

Fly ash (FA) and coal bottom ash (CBA) are by-products produced from the coal thermal plant. FA is the lighter coal ash particles that are collected from the electrostatic precipitator through FA hoppers. In comparison, CBA is the heavier coal ash particles collected from the bottom of the furnace. The coal thermal plant has produced around 20% of CBA and 80% of FA for years (Rafieizonooz *et al.*, 2016). In particular, the CBA produced from the power plant is 15-25% of the total coal ash generated (Srivastava and Singh, 2020; Yoon *et al.*, 2019). FA is widely used as SCM in concrete, but CBA is not reused at the same rate as FA. Most research incorporates CBA as cement replacement material in binary blended concrete (Argiz *et al.*, 2018; Atluri, 2016; Khongpermgoson *et al.*, 2020; Mangi *et al.*, 2019d; Oruji *et al.*, 2017).

It was known that the geopolymer containing FA required a longer setting time due to its slow reaction rate. Research from Nath and Sarker (2014) and Saha and Rajasekaran (2017) revealed significantly reduced the setting time when GGBS was incorporated in the FA-based geopolymer. Moreover, a higher reduction in setting time was observed when a higher amount of GGBS was incorporated in the geopolymer paste. A similar situation was noticed in the compressive strength performance of geopolymer paste containing FA and GGBS. Saha and Rajasekaran (2017) explained that this was due to the higher content of CaO in GGBS enhancing the formation of C-S-H gel. According to ASTM C618, a pozzolan can be categorised into 3 classes, which are Class N, Class F and Class C. Similar with FA, CBA can be classified as Class F pozzolanic material according to ASTM C618 (ASTM, 2019). Hence, there is a high potential that the positive influences of GGBS in concrete containing FA can be applied to concrete containing CBA.

It was established that the pozzolanic properties of CBA can be enhanced by pulverization of CBA. In the previous studies, pre-treatment of CBA such as sieving and calcination was conducted before grinding of CBA (Ibrahim *et al.*, 2020; Mangi *et al.*, 2019a; Mangi *et al.*, 2019b). Subsequently, the CBA was subjected to pulverization in Los Angeles machine, hammer mill, laboratory ball mill or high energy vibratory ball mill to be used as cement replacement material in concrete. During pulverization, the CBA become entrapped between the steel balls and walls, and experience constant impact fracturing which causes reduction in particle size (Oruji *et al.*, 2017).

The strength gain of the concrete can be enhanced by incorporation of high fineness FA and GGBS (6000cm^2/g) (Rivera *et al.*, 2021). While the concrete incorporating CBA with fineness of 4000cm^2/g or 5wt% retained on 45μm sieve able to achieve higher strength than full OPC (control) mix (Abdulmatin *et al.*, 2018; Mangi *et al.*, 2019c; Reddy, 2016). While mortar with GCBA of 15wt% and 25wt% retained on 45μm sieve have comparable strength with control mix at 28days (Abdulmatin *et al.*, 2018). The CBA produced at grinding period of 20 hours at Los Angeles machine or was found to have similar properties as OPC (Mangi *et al.*, 2019a).

In this research, the GCBA produced through the optimum ball mill parameters was incorporated in the OPC-GGBS-GCBA ternary blended concrete. Moreover, the physical and mechanical properties of the ternary blended concrete containing optimum GCBA were evaluated.

1.2 Problem Statement

Over the past 10 years, the global cement production was around 4 gigatons per year (IEA, 2021). The manufacture of cement is one of the main contributors to the CO_2 emissions and global warming. Hence, the consumption of cement in concrete production should be reduced.

In the meantime, the American Coal Ash Association reported that around 78 million tons of coal combustion products (CCPs) were generated in 2019 and only 53% of the CCPs were reused (ACAA, 2020). Fly ash (FA) and coal bottom ash (CBA) occupied 38% (29 million tons) and 12% (9 million tons) of the CCPs, respectively. It was observed that FA was reutilized at a rate of 62% (18 million tons) while CBA was reutilized at a rate of 33% (3 million tons). On the other hand, FA was widely used as cement replacement material in concrete production, but CBA was mostly used as cement feed for clinker and embankment applications. The coal bottom ash (CBA) has been landfilled for many years, which can cause contamination of soil and groundwater (Gooi *et al.,* 2020). Alternatives are required to promote the reutilisation rate of CBA and reduce the amount of landfilled ash. It was reported that CBA possess pozzolanic properties and can be used as partial cement replacement material in concrete production. Therefore, the properties of blended cement, mortar and concrete containing CBA were investigated in this research.

The prior research on the utilization of ground coal bottom ash (GCBA) as cement replacement material was conducted by milling CBA in a laboratory ball mill. A homogenous grind could be obtained at such a small scale of treatment but with a very high grinding energy requirement per unit output of the ground CBA material. This is because the input raw material has an extensive grading and grinding hardness spread. However, optimization of the ball mill milling parameters was not investigated to achieve the optimum output rate.

Although it was established that the GCBA could be used as pozzolanic material in mortar or concrete, however, the studies did not assess the effect of combined use of GCBA and GGBS on the properties of mortar or concrete.

In the current body of knowledge, different conclusions were reported on the influence of CBA as binder replacement materials on the properties of concrete. This is mainly because the CBA from different sources (power plants) has a significant fluctuation in terms of the grading and chemical composition of CBA. Hence, there is a need to derive comprehensive knowledge on the suitability of the CBA as binder material for concrete production.

1.3 Objectives

a) To provide a knowledge framework on the optimized milling parameters for producing GCBA in a ball mill as a constituent binder in concrete production.
b) To evaluate the properties of the binary and ternary blended cement mortar containing GGBS and GCBA.
c) To investigate the fresh and hardened properties of concrete produced with GGBS and GCBA as binder constituents.

1.4 Research Questions

a) How to obtain the optimum setting of milling operation?

b) How does the GCBA produced at optimum milling parameters affect the properties of blended cement mortar containing GGBS and GCBA?

c) What is the influence of GCBA and GGBS used as partial cement replacement materials in the production of concrete?

1.5 Scope of Works and Limitations

The milling parameters such as grinding period, degree of angular velocity (revolution per minute) and the ratio of CBA to instantaneous media were evaluated at the First Phase. Pozzolanic activity index (PAI) and slag activity index (SAI) were carried out to assess the performance of ground CBA produced from the various milling parameters. The GCBA produced from the optimum milling parameters was combined with OPC and GGBS to produce a ternary blended cement at the Second Phase of the research. The physical properties including fineness, standard consistency, soundness, setting time and compressive strength of the OPC-GGBS-GCBA blended cement were evaluated. Besides, the assessment of chemical properties such as major and minor oxide composition were carried out. The assessment on the effect of addition of PCE type chemical admixture toward the rheological, mechanical and durability performance on OPC-GGBS-GCBA ternary blended concrete was included in this research. All the tests carried out followed the American Society for Testing and Materials (ASTM), British Standard (BS), or other related standards.

This research, however, is subject to several limitations. It was reported that the performance of concrete will be influenced at elevated temperature. At temperature of over 100℃, the water in the concrete will starts to vaporize, resulting in an increased internal pressure and cracks within the concrete. Decomposition of calcium silicate hydrate (C-S-H) in concrete will be initiated at 500℃ and reach completion at 900℃. The compressive strength of concrete will be reduced as a result of decomposition of C-S-H gel (Rafieizonooz *et al.*, 2017). On the other hand, the coal ashes might consist of heavy metals that can leached to the environment. Therefore, the influence of elevated temperature on the properties of concrete containing CBA and the leaching behavior of CBA should be further investigate in the future research.

1.6 Significance of Research

Emissions of CO_2 are the major contributors to global warming. Rising demand for concrete due to the growth of the construction industry results in increased use of cement, thus putting a strain on the environment. Coal is consider as one of the world's most essential energy sources, accounting for about 40% of global electricity generation (Marto and Tan, 2016). Hence, many waste materials such as fly ash (FA) and coal bottom ash (CBA) are produced from coal thermal plants. The CBA possesses similar pozzolanic properties as FA but is not reused as SCM at the same rate as fly ash. The utilization of CBA can decrease the cost of disposal of CBA, create a cleaner and sustainable electrical power generation, reduce the global warming effect caused by the CO_2 emissions from OPC. Furthermore, it also contributes to the manufacturing of concrete in the construction industry.

Hence, the pulverized CBA was combined with ground granulated blast furnace slag (GGBS) in this research to form a ternary blended cement. The properties of the ground CBA (GCBA) and GGBS ternary blended cement, mortar and concrete were evaluated in this research. The optimum setting of milling operation able to produce GCBA at an optimum output rate. Meanwhile, the use of GCBA produced at optimum milling parameters with GGBS is expected to have positive influences on the properties of blended cement mortar. Moreover, the combined use of GCBA and GGBS is expected to enhance mechanical and durability performance of concrete.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

According to ASTM C618, a pozzolan can be categorised into Class N, Class F and Class C. The Class N and Class F should consist of more than 70% of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3). While the total composition of SiO_2, Al_2O_3 and Fe_2O_3 in the Class C pozzolan should be higher than 50%. On the other hand, the sulfur trioxide (SO_3) content, moisture content and loss on ignition (LOI) of the Class N pozzolan should be lower than 4%, 3% and 10%, respectively. The Class F and Class C pozzolan should contain less than 5%, 3% and 6% of SO_3, moisture content and LOI, respectively (ASTM, 2019).

Fly Ash (FA) and Coal Bottom Ash (CBA) are by-products produced from thermal power plants. Fly ash is widely used as supplementary cementitious material (SCM) in concrete. MS EN 450-1 (MS, 2014b) is a standard that specifies the technical specification for utilization of FA in concrete production. It was reported that high volume of FA (up to 180kg/m3) can be incorporated as cement replacement material without reducing the concrete's strength performance. Better long-term compressive strength, lower water permeable voids and absorption were observed in the binary blended concrete contain 50% (178kg/m^3) of FA when compared to binary blended concrete with 20% (67kg/m^3) of FA (Thirunagaru, 2015). Moreover, the research from Supit *et al.* (2014) reported that binary blended mortar with 40% (160kg/m^3) of FA demonstrated higher strength than full OPC (control) mortar. In contrast, Wongkeo *et al.* (2012) reported mortar with 50% (269kg/m^3) of FA had lower compressive strength than the control mortar. However, the OPC-FA blended mortar achieved higher compressive strength than control mortar by incorporation of 5 to 10% of silica fume in the blended mortar. Supit *et al.* (2014) also reported that incorporation of 8% ultrafine fly ash in mortar containing 50% to 70% (200kg/m³ to 280kg/m³) resulted in enhanced compressive strength.

CBA exhibits similar pozzolanic properties as FA and can be classified as Class F pozzolanic material according to ASTM C618 (ASTM, 2019). However, CBA is not reutilized at the same rate as FA in concrete production. The research from Oruji *et al.* (2017) indicated that the binary blended mortar containing 9% to 41% (45kg/m³ to 203kg/m³) of Ground Coal Bottom Ash (GCBA) exhibited higher compressive strength than control mortar and binary blended mortar with 9% to 41% (45kg/m³ to 203kg/m³) of FA at 28 to 90 days. Incorporation of FA and CBA in the blended mortar had resulted in reduced drying shrinkage and autogenous shrinkage compared to the control mortar (Wongkeo *et al.*, 2012).

The physical properties and chemical composition of CBA from various studies were discussed in this chapter. In addition, the fresh and hardened properties of mortar or concrete containing GCBA as SCM were condensed in table form for the ease of comparison between various studies. The fresh properties such as setting time and workability and hardened properties such as compressive strength, permeable voids, water absorption, porosity and resistance of concrete with CBA to chemical attack are covered in this chapter.

A summary of the test method is essential to provide a better understanding regarding the method used by various researchers to evaluate the properties of mortar or concrete with CBA. There are various methods of processing CBA for use as cement replacement material. For instance, CBA processed with different refinement methods can be utilized as SCM in binary, ternary or quaternary blended concrete at various replacement levels. Hence, a summary of the CBA processing method is provided in this chapter to give an overall view of the type of CBA-blended mortar or concrete, refinement method, and replacement level of CBA in mortar or concrete. Besides, various water to binder ratio and sand to binder ratio used in different studies are shown in the summary of test method.

2.2 Physical Properties of Coal Bottom Ash

Generally, the physical properties of CBA were primarily influenced by the type of processing method of CBA. The increased grinding period will increase the specific gravity, mean particle size, specific surface area and percentage of CBA retained at 45µm sieve due to the increased fineness of CBA particles. The efficiency in producing finer CBA particles was also influenced by the type of grinding machine used for the pulverization of raw CBA. For instance, the CBA ground by high-energy vibratory ball mill for 3 hours had higher fineness than the CBA ground by Los Angeles machine for 40 hours (Mangi *et al.*, 2019c; Oruji *et al.*, 2019; Oruji *et al.*, 2017). A high-efficiency grinding machine able to produce finer CBA with enhanced physical properties while minimizing energy wastage.

Table 2.3 shows that the specific gravity (SG) of ground CBA (GCBA) were ranged from 2.36 to 2.94 while the SG of original CBA (OCBA) were ranged from 1.80 to 2.33. It was observed that the SG of GCBA will increase with the increased grinding period of CBA. For instance, the SG of GCBA increased from 2.36 to 2.50 when the grinding period increased from 2 hours to 40 hours (Mangi *et al.*, 2019a). Besides, the increased % of GCBA retained on 45µm sieve from 3.7% to 43.7% led to reduced SG of GCBA from 2.88 to 2.72. It is an indication that GCBA with higher fineness would have a higher SG value than those with lower fineness. Hence, the unground OCBA showed SG value of only 2.33 (Abdulmatin *et al.*, 2018).

The median diameter (d_{50}) of GCBA was found to range between 2.4µm to 72.3µm. Generally, the d_{50} of the GCBA is lower with the increased fineness of GCBA. The d_{50} of GCBA increased from 4.3µm to 72.3µm when the % of GCBA retained on 45µm increased from 3.7% to 43.7% (Abdulmatin *et al.*, 2018). Oruji *et al.* (2019) also indicated that GCBA with grinding period of 0.5 and 3 hours have d_{50} of 6.3µm and 4.5µm, respectively. Meanwhile, the d_{50} of unground CBA ranged from 400µm to 731µm (Abdulmatin *et al.*, 2018; Kasaniya *et al.*, 2021).

Furthermore, the specific surface area (SSA) of GCBA were varied from 210m²/kg to 1101.9m²/kg. Similar to the SG of GCBA, the SSA of GCBA increased with the increased fineness of GCBA. For instance, the SSA of GCBA increased from 383.6m²/kg to 463.8m²/kg as the grinding period increased from 20 to 40hours (Mangi *et al.*, 2019c). However, there were contradicting findings of SSA of GCBA when the grinding period of GCBA was increased. Oruji *et al.* (2017) and Oruji *et al.* (2019) indicated that GCBA with grinding period of 3hours has SSA of 1101.9m²/kg. Mangi *et al.* (2019c) and Mangi *et al.* (2019a) showed that GCBA with grinding period of 40 hours has SSA of only 463.8m²/kg. This was mainly due to different types of pulverization machines were used in these research. According to Oruji *et al.* (2017) and Oruji *et al.* (2019), a high-energy vibratory ball mill with an angular velocity of 1200 rotational/min was used. During pulverization of CBA, the ball mill will rotate around its horizontal axis and vibrate around its vertical axis. It also stated that the CBA powder to steel media ratio was 1:3 by mass. Meanwhile, the Los Angeles (LA) machine was used to pulverise raw CBA for 2 hours (Mangi *et al.*, 2019a; Mangi *et al.*, 2019c). The CBA that ground for 2hours was subjected to up to 40hours grinding in ball mill grinder. The total mass of steel ball and CBA powder filled in ball mill were 1500g and 2500g, respectively. The high energy vibratory ball mill able to pulverize raw CBA more efficiently if compared to the ball mill grinder. This was due to the high energy vibratory ball mill able to move in both rotational and vibratory movement at 1200 rpm. Besides, smaller amount of CBA (25g) was subjected for each pulverization in high energy vibratory ball mill. The steel ball in the high energy vibratory ball mill able to break up the CBA particles more effectively. In addition, excess pulverization of CBA might results in coagulation of CBA particles and causes reduction in fineness of CBA particles.

Table 2.1 Physical Properties of Coal Bottom Ash

Reference	Type of binder	Specific gravity	Mean particle size,d_{50} (µm)	Specific surface area (m^2/kg)	Retained on 45µm sieve (%)
(Khongpermgoson *et al.*, 2019)	GCBA	2.88			3.70
(Mangi *et al.*, 2019a)	2 – 40H GCBA	2.36 – 2.50		234.8 – 463.8	
(Oruji *et al.*, 2019)	0.5 – 3H GCBA	2.81	6.3 – 4.5	858.6 – 1101.9	
(Khongpermgoson *et al.*, 2020)	Ultra-fine GCBA	2.76			2.89
(Mangi *et al.*, 2019c)	20H GCBA	2.41		383.6	
(Demir *et al.*, 2018)	GCBA			435.0	
(Argiz *et al.*, 2018)	GCBA	2.65		809.3	3
(Wongkeo *et al.*, 2012)	GCBA	2.70	7.81		
(Pliatsikas *et al.*, 2019)	GCBA	2.52		395	
(Abdulmatin *et al.*, 2018)	GCBA	2.88 – 2.72	4.3 – 72.3		3.7 – 43.7
	OCBA	2.33	400		96.3
(Xie and Ozbakkaloglu, 2015)	GCBA		54		
(Sata *et al.*, 2012)	Fine BA	2.89	15.7	500	3
	Medium BA	2.87	24.5	340	18
	Coarse BA	2.86	32.2	210	33
(Ibrahim *et al.*, 2015)	GCBA			316	
(Mangi *et al.*, 2019b)	20 – 40H GCBA	2.41 – 2.50		383.6 – 463.8	
(Kasaniya *et al.*, 2021)	GCBA	2.80	2.4		
	OCBA	1.80	731		
(Logesh Kumar and Revathi, 2016)	12H-GCBA	2.17		346	
(Nguyen *et al.*, 2017)	0.5H-GCBA		32.11		
(Pormmoon *et al.*, 2021)	GCBA produced by different	2.86 – 2.88			5.35 – 5.97

Table 2.1 Continued

	OCBA size				
(Hong and Kim, 2019)	GCBA		37.55		
(Hussain *et al.*, 2020)	10H GCBA	2.3		363.6	
(Lo *et al.*, 2021)	-	2.94	22.97		1
(Abbas *et al.*, 2020)	Passed 75µm sieve	2.35		435.5	< 5
(Nafissatou Savadogo *et al.*, 2020)	GCBA passed through 80µm sieve	2.31	16.17	410.9	

2.2 Chemical Composition of Coal Bottom Ash

The chemical requirement for a pozzolan to be classified as Class F pozzolanic material is prescribed in ASTM C618 (ASTM, 2019). A Class F pozzolan should contain a minimum of 70% SiO_2+Al_2O_3+Fe_2O_3, a maximum of 5% SO_3, a maximum of 3% moisture content and a maximum of 6% loss on ignition.

The chemical properties of the CBA were influenced by the method of pre-processing the CBA before grinding. Research from Pormmoon *et al.* (2021) revealed that sieving before grinding CBA can increase the amorphous content of CBA. Increased amorphous content was observed at a higher fineness of OCBA. The original CBA (OCBA) that sieved through a 9.53mm sieve has amorphous content of 39.29%. However, the OCBA that passed and retained through 4.76mm – 0.297mm sieve has amorphous content of 46.03 – 51.52%. Meanwhile, research from Lo et al. (2021) involved calcination of CBA at 1100°C before grinding. It was observed that the SiO_2 content in CBA decreased from 79% to 74% after calcination. In contrast, the amount of Al_2O_3 in CBA increased from 16% to 45% after calcination. According to Kusbiantoro *et al.* (2019), the SiO_2 in CBA pre-treated with 0.5M of sulfuric acid increased from 42.64% to 49.40%. Moreover, it was noticed that the MgO and Na_2O in CBA was eliminated after CBA was pre-treated with H_2SO_4.

The chemical composition of fly ash (FA) and coal bottom ash (CBA) are shown in Table 2.4 and Table 2.5, respectively. In Table 2.4, a study reported the total % of SiO_2, Al_2O_3 and Fe_2O_3 of less than 70% (Demir *et al.*, 2018). Meanwhile, most of the reported works showed total % of SiO_2, Al_2O_3 and Fe_2O_3 of more than 70%. The total % of SiO_2, Al_2O_3 and Fe_2O_3 in FA ranged from 63.93 to 90.47%, with an average value of 82.56%. Meanwhile, the average value of SiO_2, Al_2O_3 and Fe_2O_3 was 50.83%, 24.01% and 7.72%, respectively. The SO_3 content in FA was less than 5%, which varies between 0.8 to 2.64%, with an average value of 1.79%. Similarly, FA's LOI content was less than 6%, which varies from 0.8 to 2.4%, with an average value of 1.72%. The minor oxide composition in FA were CaO, TiO_2, K_2O, MgO, P_2O_5 and Na_2O, with an average value of 6.08%, 1.21%, 2.35%, 2.42%, 1.96% and 1.43%, respectively.

In Table 2.5, most studies indicated that the total % of SiO_2, Al_2O_3 and Fe_2O_3 of CBA was more than 70%. Only a few studies showed total % of SiO_2, Al_2O_3 and Fe_2O_3 of less than 70%, which were 65.69%, 63.64%, 54.50%, 55.77%, 56.17% and 49.80% (Abbas *et al.*, 2020; Demir *et al.*, 2018; Hanjitsuwan *et al.*, 2017; Ibrahim *et al.*, 2015; Pormmoon *et al.*, 2021; Suksiripattanapong *et al.*, 2020). Hence, the total % of SiO_2, Al_2O_3 and Fe_2O_3 of CBA ranged from 49.80 to 92.14%, with an average value of 76.03%. The average value of SiO_2, Al_2O_3 and Fe_2O_3 were 47.66.%, 18.84% and 9.53%, respectively. Besides, most studies revealed that the SO_3 content in CBA was less than 5%. However, some studies used CBA with more than 5% of SO_3 content, which were 5.19%, 6.29% and 10.15% (Demir *et al.*, 2018; Logesh Kumar and Revathi, 2016; Suksiripattanapong *et al.*, 2020). The SO_3 content varies from 0.4 to 10.15%, with an average value of 1.61%. Meanwhile, there were also works of literature reported that LOI values of higher than 6%, which were 7.68%, 8.61% and 10.85% (Abbas *et al.*, 2020; Hanjitsuwan *et al.*, 2017; Nguyen *et al.*, 2018; Nguyen *et al.*, 2017). The rest of the papers have LOI content of lower than 6%. The LOI content was varied from 0.5 to 10.85%, with an average value of 3.33%. The minor composition in CBA were CaO, TiO_2, K_2O, MgO, P_2O_5 and Na_2O, with an average value of 9.64%, 0.66%, 1.47%, 1.96%, 0.52% and 0.90%, respectively.

In conclusion, CBA exhibits similar chemical composition with FA. Both CBA and FA fulfil the chemical requirement stated in ASTM C618 to be classified as Class F pozzolanic material. Except for the CBA contained 54.50%, 55.77% and 56.17% of

$\sum SiO_2+Al_2O_3+Fe_2O_3$, it can be classified as Class C pozzolanic material according to ASTM C618.

Table 2.2 Chemical Composition of Fly Ash

Fly ash	Chemical composition (%)															
	SiO_2	Al_2O_3	Fe_2O_3	**Total %**	CaO	TiO_2	K_2O	MgO	SrO	P_2O_5	SO_3	BaO	ZrO_2	Na_2O	MnO	LOI
(Oruji *et al.*, 2019)	50.77	26.65	10.06	**87.48**	5.11		0.61	2.15			1.20			0.77		1.08
(Oruji *et al.*, 2017)	52.00	23.00	11.00	**86.00**	5.0		2.00				0.80			1.00		0.80
(Demir *et al.*, 2018)	45.37	11.16	7.40	**63.93**	14.15		4.19	4.69		8.28	2.64			2.07		1.48
(Argiz *et al.*, 2018)	54.60	28.80	5.30	**88.70**	1.40	1.03	3.72	1.89		0.17				0.37		2.40
(Wongkeo *et al.*, 2012)	45.37	20.65	12.31	**78.33**	10.43	0.52	1.50	2.13		0.25	2.53			1.33		3.00
(Xie and Ozbakkaloglu, 2015)	49.00	31.00	3.00	**83.00**	5.00	2.00	1.00	3.00		1.00				4.00		
(Jaramillo Nieves *et al.*, 2020)	58.7	26.8	4.97	**90.47**	1.49	1.28	3.41	0.65		0.12				0.44		1.54
(Lo *et al.*, 2021)	78.96	0.19	5.72	**84.87**	13.36	0.34	0.51				1.06					4.21
AVERAGE	50.83	24.01	7.72	**82.56**	6.08	1.21	2.35	2.42	0	1.96	1.79	0	0	1.43	0	1.72

Table 2.3 Chemical Composition of Coal Bottom Ash

Coal bottom ash	Chemical composition (%)															
	SiO_2	Al_2O_3	Fe_2O_3	**Total %**	CaO	TiO_2	K_2O	MgO	SrO	P_2O_5	SO_3	BaO	ZrO_2	Na_2O	MnO	LOI
(Mangi *et al.*, 2019a); (Ibrahim *et al.*, 2020)	52.50	17.65	8.30	**78.45**	4.72	2.17	0.83	0.58	0.20	0.29	0.84	0.17	0.14	0.16		4.01
(Hanjitsuwan *et al.*, 2017)	26.17	15.79	14.21	**56.17**	28.51	0.31	1.43	2.98		0.25	1.50			1.05	0.12	7.68
(Khongpermgoson *et al.*, 2019)	35.60	19.60	14.90	**70.10**	18.70		2.30	2.40			1.70					3.60
(Oruji *et al.*, 2019)	58.73	20.07	6.22	**85.02**	9.51		0.97	1.64			0.42			0.12		0.79
(Khongpermgoson *et al.*, 2020)	36.50	20.0	15.10	**71.60**	18.70		2.50	1.90			2.90			0.20		3.6
(Oruji *et al.*, 2017)	58.70	20.10	6.20	**85.00**	9.50		1.00	1.70			0.40			0.10		0.80
(Mangi *et al.*, 2019c); (Mangi *et al.*, 2019d)	52.50	17.65	8.30	**78.45**	4.72	2.17		0.58			0.84					4.01
(Demir *et al.*, 2018)	37.45	9.03	8.02	**54.50**	18.08		1.88	5.79		11.75	6.29			1.67		2.82
(Argiz *et al.*, 2018)	52.40	27.50	6.60	**86.50**	2.40	0.97	3.48	1.83		0.12				0.36		3.80
(Wongkeo *et al.*, 2012)	47.59	19.1	14.34	**81.03**	10.16	0.31	1.21	1.48		0.16	2.44			1.08		2.12

Table 2.3 Continued

(Chaipanich and Wongkeo, 2014)	39.56	22.48	14.93	**76.94**	15.54	0.46	1.76	2.54		0.19	0.65			0.77	0.12	1.00
(Pliatsikas *et al.*, 2019)	49.22	18.82	8.25	**76.29**	13.85	0.81	0.53	3.22			1.18			1.54	0.02	2.27
(Abdulmatin *et al.*, 2018)	35.60	19.60	14.90	**70.10**	18.70		2.30	2.40			1.70			1.20		3.60
(Xie and Ozbakkaloglu, 2015)	54.00	25.00	4.00	**83.00**	5.00	2.00	1.00	2.00		1.00				3.00		2.00
(Suksiripattanapong *et al.*, 2020)	36.33	13.71	15.65	**65.69**	21.76		1.20				10.15					0.50
(Mangi *et al.*, 2019b)	53.80	18.10	8.70	**80.60**	5.30	1.20	0.85	0.58	0.35	0.29	0.90	0.18	0.15	0.17		4.02
(Ibrahim *et al.*, 2015)	34.10	9.31	12.39	**55.77**	11.88		0.51	5.28			0.91			0.12		
(Kasaniya *et al.*, 2021)	52	19.4	9.1	**80.5**	8.8	1.1		1.5			0.4			0.9		1.5
(Antunes Boca Santa *et al.*, 2013)	59.8	25.2	4.5	**89.5**	1.3	1.1	2.3	0.5								6.6
(Logesh Kumar and Revathi, 2016)	51.5	32.58	-	**84.08**	0.50		0.58	0.21			5.19			1.35		1.50
(Nguyen *et al.*, 2017); (Nguyen *et al.*, 2018)	52.63	20.85	9.08	**82.56**	0.82	1.39	4.75	0.90			0.75			0.22		8.61
(Pormmoon *et al.*, 2021)	36.47-37.12	17.66-17.87	8.65-8.91	**63.05-63.64**	15.95-17.23		1.88 - 1.98	2.05 - 2.14			1.49 - 2.72			1.18-1.22		
(Paija *et al.*, 2020)	50.80	12.40	22.70	**85.90**	6.81	0.57	1.31	0.73		0.06	0.47	0.02		1.43		

Table 2.3 Continued

(Jaramillo Nieves *et al.*, 2020)	60.5	24.2	4.68	**89.38**	1.22	1.09	2.84	1.15						0.48		3.55
(Hong and Kim, 2019)	50.7	20.3	11	**82**	7.65	1.32	1.75	1.56						7.65		2.28
(Kusbiantoro *et al.*, 2019)	42.64	15.41	17.88	**75.93**	11.81		1.27	11.81		1.29	1.44			1.72		
(Hussain *et al.*, 2020)	51.50	14.30	5.08	**70.88**	1.28	0.91	0.99	0.47						0.19		
(Lo *et al.*, 2021)	73.26	15.77	3.11	**92.14**	7.42	0.20	0.13				0.08					3.25
(Abbas *et al.*, 2020)	33.85	11.20	4.75	**49.80**	7.65		0.52	0.51			4.88			0.13		10.85
(Nafissatou Savadogo *et al.*, 2020)	53.2	22.2	4.36	**79.76**	0.41	1.67	1.90	0.56	0.01	0.04	0.30			0.22		15
AVERAGE	**46.01**	**20.72**	**10.40**	**76.73**	**10.43**	**1.13**	**1.83**	**1.90**	**0.28**	**1.57**	**2.09**	**0.12**	**0.15**	**0.79**	**0.09**	**3.45**

2.3 The Method of Processing Coal Bottom Ash for Use as Cement Replacement Materials in Concrete/Mortar

The raw CBA is less suitable for cement replacement material because the coarser CBA particles have limited pozzolanic reactivity. The consumption of calcium hydroxide was higher in a mortar containing finer CBA particles than full OPC mortar and mortar with coarser CBA particles (Oruji *et al.*, 2017). This indicates that the higher fineness of CBA able to increase the pozzolanic reactivity (Mangi *et al.*, 2019a; Oruji *et al.*, 2019). It was also reported that the finer CBA enhanced the concrete matrix filling and calcium absorption (Oruji *et al.*, 2019). Therefore, the raw CBA was pulverized in the Los Angeles machine, hammer mill, laboratory ball mill or high energy vibratory ball mill before being used as cement replacement material. The raw CBA was ground at a pre-determined grinding period or until the required fineness of CBA was achieved.

As shown in Table 2.4, majority of the reported studies used CBA as a cement replacement material in binary blended cement paste, mortar, or concrete. Demir *et al.* (2018), Wongkeo *et al.* (2012), Pliatsikas *et al.* (2019) and Lo *et al.* (2021) reported the use of CBA in ternary or quaternary blended mortar. Fly ash (FA), rice husk ash (RHA) and demolition ceramic waste (DCW) were combined with CBA in ternary blended cement system (Lo *et al.*, 2021; Pliatsikas *et al.*, 2019; Wongkeo *et al.*, 2012). Meanwhile, FA-GGBS and FA-silica fume (SF) was combined with CBA in a quaternary blended cement system (Demir *et al.*, 2018; Wongkeo *et al.*, 2012).

The grinding period of CBA ranged from 0.5 to 48 hours (h). Some reported studies also ground the CBA to the fineness of 2.89 – 45wt% of GCBA retained on 45µm test sieve (Abdulmatin *et al.*, 2018; Argiz *et al.*, 2018; Khongpermgoson *et al.*, 2019; Khongpermgoson *et al.*, 2020).