Effects of Grinding Process on the Properties of the Coal Bottom Ash and Cement Paste

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Abstract. The grinding process is necessary to convert original coal bottom ash (CBA) into a powder form. The aim of this study is to evaluate the grinding process effects on physical properties of CBA, it influences on consistency and setting time of cement paste and to predict it potentiality based on chemical characteristics to reduce the alkali-silica reaction (ASR) in concrete. The CBA is the by-product of coal based thermal power plant. Due to high production of electricity in Malaysia, the excess amount of CBA has been produced annually and it causes the environmental problems. Therefore, it is necessary to come up with advanced solutions for that pollution. This study considered the different grinding periods i.e. 2, 10, 20, and 40hrs as to produce different particle fineness. It was perceived through the laboratory findings that the more the grinding period, finer the particle sizes. Besides that, cement paste with 10, 20 and 30% of ground CBA as a substitute of ordinary portland cement (OPC) by weight was prepared, it was observed that the consistency of OPC paste increases with the addition of ground CBA. Moreover, initial and final setting time of cement paste containing ground CBA was observed higher than the OPC paste. Hence, based on experimental analysis and energy efficiency scenario, grinding period of 20hrs with specific surface area 3835.75 cm^2/g is suggested for the future studies.

Keywords: *cement replacement; coal bottom ash; grinding effects; particle fineness; setting time.*

1 Introduction

Currently, many studies have been conducted on the effective use of industrial by-products like fly ash [1], Palm oil fuel ash [2], sugarcane bagasse ash [3] silica fume, bottom ash [4] as a construction material but the coal bottom ash is

Received January 21st, 2018, Revised July 29th, 2018, Accepted for publication January 10th, 2019.
 ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.1.1

the most recent, because of the high production of coal combustion residues [5]. Coal bottom ash (CBA) is the by-product of the pulverized coal in power plants. It has large particle size and porous in nature [6] as shown in Figure 1. Its application in the field of civil engineering has the great environmental advantages, which are noteworthy in the sustainability of natural resources [7]. However, limited research is reported on the application of CBA as a supplementary cementing material (SCM) and particularly very less literature is reported on the effects of grinding process on the properties of CBA.

Figure 1 Particles of original CBA

Formerly, several attempts were made to utilize CBA in the production of concrete. whereas, Singh & Siddique in [8] and [9] investigated on the possible use of CBA as partial replacement of sand (fine aggregate) in concrete and presented physical properties and mechanical performances of concrete containing CBA as fine aggregate. Furthermore, Siddique, [10] studied the properties of self-compacting concrete (SCC) made with CBA as partial replacement of fine aggregates.

Baite, *et al*., [5] studied the thermal performances of CBA as partial or full replacement of river sand in mortar and it was found that CBA in mortar mix decreases the thermal conductivity up to 64% as compared with the control mix sample. There are limited papers that discussed about the CBA as a cement replacement material. furthermore, it was recommended by Kim, *et al.* [11] that CBA has great tendency to be act as pozzolanic material, resulting in improvement of durability of the concrete. Earlier, it was also perceived that the use of CBA reduces the permeability of water through mortar [5]. The findings of Cheriaf, *et al.* [12] indicated that the pozzolanic activity of CBA was found to be increased while increasing the grinding period. The strength and durability performances of concrete are mainly depending upon the properties of supplementary cementing materials.

Besides that, Alkali silica reaction (ASR) is also a prominent issue in concrete, which could be minimized through introducing supplementary cementing materials. The previous studies on fly ash indicated the beneficial effect on ASR and its mitigation, it was found that major influence on ASR mitigation due to of chemical composition [13-15]. It was also stated by Shehata and Thomas [13, 15] that the influence of fly ash chemical composition on ASR mitigation shows low-lime fly ashes (CaO < 8%) were more effective than the high-lime fly ashes (CaO > 20%) and required lower replacement levels for ASR mitigation. However, properties of CBA based on lime content alone may not be proper as other oxides in CBA can also increase or decrease ASR growth. It was also suggested by Malvar, *et al.* [16] that fly ash efficacy in mitigating ASR can be better categorized by considering a chemical content that is based on available oxides in fly ash, rather than simply on the lime content present in the ash. The lime content of coal bottom ash is varies according to the geographic locations, which affects the ASR reaction, available practices such as grinding or sieving can be employed to reduce their average particle size to appropriate size so as to achieve ASR mitigation [17].

The utilization of available resources and methods to mitigate ASR can avoid the need to transport extra materials from other locations, thereby eradicating the material transportation cost, and thus providing a sustainable alternative for ASR mitigation. Hence, considering the importance of chemical composition of CBA and its fineness for better performances as a cementitious material has been perceived from the literature, none of above studies were discussed on grinding effects on the properties of CBA and its potentiality. The significance and novel outcome of this article is to assess the influence of grinding process on the CBA properties and the reason to conduct this research is set forwarded as:

1. To understand the effects grinding process on particle size, surface area and specific gravity.
2. To identify the suitable grinding period / particle size / specific surface area for the better performance of ground CBA as a supplementary cementitious material.
3. To predict the potentiality of CBA in mitigating ASR directly from its chemical composition.
4. Influence of particle fineness of ground CBA on the consistency and setting time of cement paste.

2 Materials and Methods

The Coal bottom ash (CBA) used in this study was collected from Sultan Salahuddin Abdul Aziz Power Plant also known as Kapar Energy Vetures, Selangor, Malaysia and Ordinary Portland cement conforming to ASTM Type I and Malaysian Standard MS 522 was used in this study. The collected original coal bottom ash was dried in an oven at a temperature of 110±5 °C for 24 hours, then original CBA was placed in loss Angeles (LA) machine for the period of 2hrs as shown in Figure 2, afterward ground CBA passed through 300micron sieve and proceed for the more grinding in a ball mill grinder for the varying time periods i.e. 10, 20, and 40 hrs. as shown in Figure 3. The same size (50mm in diameter) of 6 steel balls and varied size of 6 steel bars were used in Los Angeles (LA) machine as shown in Figure 4. But in ball mill grinder, unusual sizes of steel balls were used to ensure the effective grinding as shown in Figure 5. The details of grinding media such as number of balls, ball weight, ball diameter and powder filling are provided in Table 1.

Figure 2 Los Angeles machine.

Figure 3 Ball mill grinder.

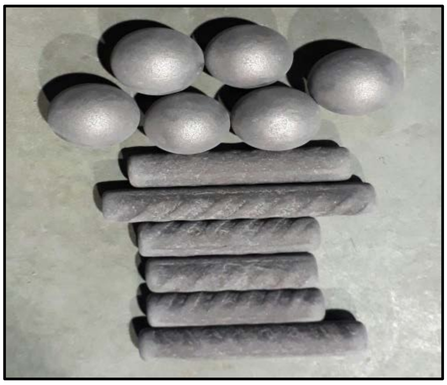

Figure 4 Balls and bars in Loss Angeles machine.

Figure 5 Balls in ball mill grinder.

Table 1 Detail of grinding media.

Ball diameter (mm)	**Number of balls**	**Ball weight (grams)**	**Powder filling (grams)**
46	1	397	2500
47	1	425	
50	1	548	
25	8	60	
20	25	30	
15	25	15	
14	22	10	
11.5	23	7	

Form each grinding period the representative samples were taken for particle size analysis (PSA) and scanning electron microscope (SEM) images. Beside that a cumulative sample was prepared for the chemical analysis through X-ray fluorescence (XRF) test. In this study, CBA was ground into four varied sizes and manually sieved through 63micron to assess the fineness particles and results are as under;

1. CBA 2: the coal bottom ash was grinded for 2hrs in Los Angeles (LA) Abrasion Machine and get 30.07% passing from 63micron sieve.
2. CBA10: the coal bottom ash was grinded for 10hrs in ball mill grinder and get 50.75% passing from 63micron sieve.
3. CBA20: the coal bottom ash was grinded for 20hrs in ball mill grinder and get 65.47% passing from 63micron sieve.
4. CBA40: the coal bottom ash was grinded for 40hrs in ball mill grinder and get 85.73% passing from 63micron sieve.

3 Results and Discussions

3.1 Grinding Effects on Physical Properties

The grinding process effect on physical properties of CBA was evaluated through advanced particle size analyzers instrument (CILAS1180) as shown in Figure 6, the particle size, specific surface area of ground CBA were investigated at different grinding periods. CILAS1180 have capacity to measure of particles size between 0.04 and 2,500 µm. For the instance four sample of CBA with different grinding periods were determined for specific surface area as 2347.73, 3721.92, 3835.75, 4637.78cm^2/g for 2, 10, 20, and 40hrs. grinding period respectively. Beside that the specific surface area of OPC were obtained as 4870.81 cm^2/g. While comparing the results of ground CBA obtained through 20 and 40hrs. were found to be comparable properties as OPC, but considering the economic scenario 20hrs was found to suitable to replace the cement for the future studies. It is worth noted here that the fineness and particle surface area of the CBA increases as the grinding time increases.

Figure 6 Particle Size Analyzer (Model CILAS1180).

The particle sizes of ground CBA were determined through particle size analyzer model no. CILAS1180, which shows the physical properties of ground CBA and OPC such as range of particle sizes, specific gravity and results are provided in Table 2. Whereas, Cheriaf *et al.*, [12] investigated that average particle size of ground CBA as 35 µm for the grinding period of 1 to 6hrs.

Table 2 Physical properties of ground CBA and OPC.

Sample Code	Grinding Period (Hrs)	Specific gravity	Range of Particle Size (Micron)			Specific Surface Area (cm^2/g)
			D10	D30	D60	
CBA_2	2	2.36	8.20	34.22	100.95	2347.73
CBA_{10}	10	2.40	4.01	22.57	76.90	3721.92
CBA_{20}	20	2.44	3.65	18.57	50.45	3835.75
CBA_{40}	40	2.50	2.79	15.44	46.12	4637.78
OPC	Original	3.10	3.81	12.55	21.15	4870.81

3.2 Chemical Properties of Ground CBA

The chemical composition of the bottom ash was determined by using X-ray fluorescence (XRF) method on 8g of bottom ash and 2g of wax powder. From the X-ray fluorescence (XRF) the main chemical compounds include Silicates (SiO_3), Aluminates (Al_2O_3) and Iron oxide (Fe_2O_3) with a host of other compounds in smaller percentages were determined. The chemical composition of ordinary Portland cement (OPC) and the coal bottom ash obtained conducted on ground bottom ash that collected from thermal power stations in Selangor, Malaysia were evaluated, and results are presented in Table 3.

Table 3 Chemical properties of OPC and ground CBA.

Sample Notation	**OPC**	**CBA**
Chemical Content	%	%
Silica / Silica dioxide (SiO_2)	20.61	52.50
Alumina / Aluminium Trioxide (Al_2O_3)	3.95	17.65
Iron / Ferric Oxide (Fe_2O_3)	3.46	8.30
Lime content / Calcium Oxide (CaO)	63.95	4.72
Titanium dioxide (TiO_2)	0.20	2.17
Carbon (C)	-	0.10
Potassium Oxide (K_2O)	-	0.83
Magnesia / Magnesium Oxide (MgO)	1.93	0.58
Strontium oxide or strontia (SrO)	-	0.20
Phosphorus pentoxide (P_2O_5)	-	0.29
Sulfur trioxide (SO_3)	3.62	0.84
Barium oxide (BaO)	-	0.17
Zirconia/ Zirconium dioxide (ZrO_2)	-	0.14
Sodium superoxide (Na_2O)	-	0.16
Loss on ignition (LOI)	2.18	4.01

The chemical composition of ground coal bottom ash obtained through grinding periods are found as a pozzolanic materials of Class F as prescribed by ASTM C618 [18]. Since the sum of components SiO_3, Al_2O_3, and Fe_2O_3 is greater than 70%. The sum of silica, alumina and ferric is the key indicator that represents the pozzolanic activity of the material [18, 19]. Whereas, the loss on ignition (LOI) and SO_3 content are not higher than 5% and 6% respectively, similar result has been reported by Cheriaf, *et al.* [12]. Beside that the particle size has less role than the chemical composition in ASR mitigation [17]. It was also previously validated that when the average particle size of CBA less than 10 microns, the fineness becomes more significant in ASR mitigation [17]. Therefore, higher strength was reported for the mixtures with SiO_2/Al_2O_3 (SA) ratios in the range of 3.0–3.8 [20]. Whereas, variations in the SA ratio beyond this range found as low strength structures [21, 22]; thus, the ground CBA was observed based on oxides contains in the sample. Since, chemical analysis results; the silica- alumina (SA) ratio has been calculated from the below Eq.(1) as 2.9745 say 3 for ground CBA which is also fall within the range as mentioned above.

$$\text{SA Ratio} = \frac{\text{SiO2}}{\text{Al2O3}} \tag{1}$$

Therefore, considering the energy efficiency scenario, the grinding period of 20 hrs. for CBA has been suggested for future studies on its utilization in concrete as supplementary cementing material. Furthermore, silica modulus (SM) is the important ratio that indicates the quality of cement clinker / supplementary cementing material. The typical ranges of silica modulus are 1.8 to 2.7.

$$SM = \frac{SiO2}{Al2O3+Fe2O3} = \frac{54.40}{18.30+8.85} = 2.0 \quad (2)$$

The theoretical calculation obtained through Eq.(2), silica modulus was calculated as 2.0, which is also within the required range.

3.3 Ground CBA Potentiality Prediction for ASR Mitigation

In this study, the combined effect of CaO + MgO + SO_3 and SiO_2 + Al_2O_3 + Fe_2O_3 on alkali silica reaction (ASR) mitigation was predicted through Eq.(3), it was previous adopted by Venkatanarayanan and Rangaraju [17] for fly ash and they declared that higher the ratio more the ASR action and for mitigating ASR action, ratio should be below than 0.22 [17].

$$ASR = (CaO + MgO + SO_3)/(SiO2 + Al_2O_3 + Fe_2O_3) \quad (3)$$

The ratio of ASR obtained through Eq.(3), shows that in all ashes the value of ASR is lower than the 0.22. It was calculated as 0.078 for ground CBA obtained through grinding process, which indicated the potentiality of ground CBA to mitigate the alkali silica reaction (ASR) in concrete.

3.4 Particle Fineness Effect on Setting Time

The normal consistency, initial and final setting results for different mix proportions were evaluated. Whereas, ground CBA was utilized as partial replacement of cement at 10, 20 and 30% by weight of cement. The results are illustrated in Figure 7. The normal consistency of cement paste was 30%, with initial and final setting time of 90 and 270 minutes respectively. The normal consistency of ground CBA at different replacement and different fineness were evaluated and found between 32 to 37% and the initial and final setting time is 10 to 45 minutes higher than the cement paste. While comparing the results with cement paste, almost similar values were observed with 10% cement replacement with CBA 10, 20 and 40hrs. It was generally perceived that consistency of paste increases with increase in cement replacement level with ground CBA. The consistency was found to be increased because ground CBA absorbed more water than the normal cement paste [24, 25]. Since the replacement of cement with ground CBA reduces the amount of tri-calciumsilicate (C_3S) in paste thus resulting in longer setting time in the cement paste [26].

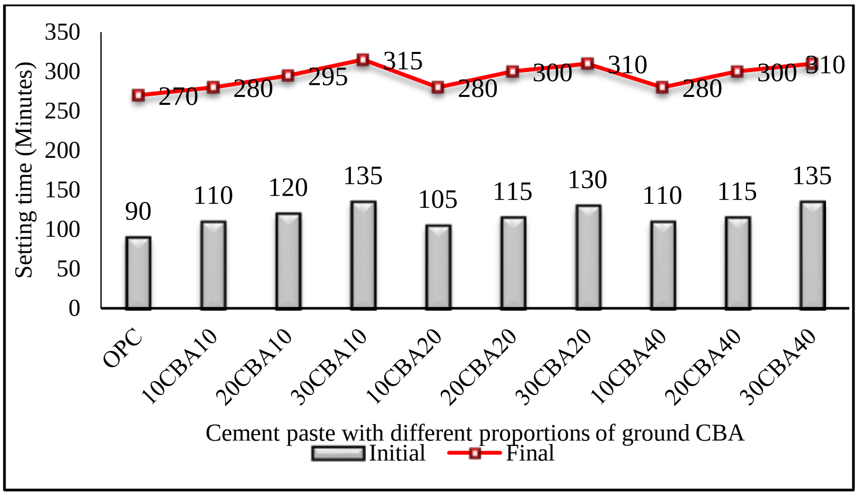

Figure 7 Initial and final setting time of cement paste containing ground CBA.

3.5 Scanning Electron Micrograph of CBA

Scanning electron microscopy (SEM) helps to understand the concrete microstructure. The SEM test was conducted for the examination and analysis of the microstructural characteristics of solid objects includes characterization of Nano-materials The SEM image of original CBA has revealed that it has porous nature, irregular and sharp particles and substantial number of voids was noticed during morphological analysis as shown in Figure 8. This indicated the presence of voids and particle shapes. Furthermore, Cheriaf, *et al.* [12] also reported that original CBA has rounded and irregularly shaped particles.

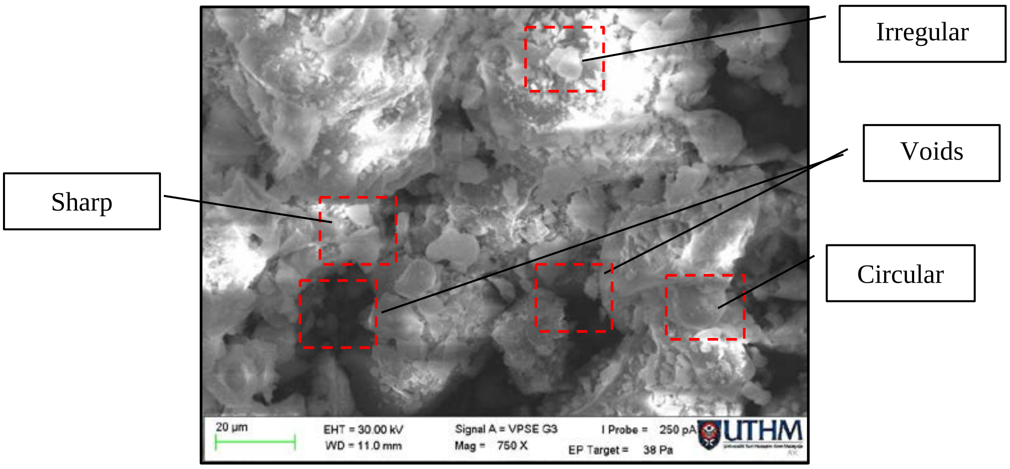

Figure 8 Scanning electron microscope image of Original CBA

Apart from original CBA, the morphological image of OPC and ground CBA10, CBA20, CBA40 are provided Figure 9 to describe the microstructure of the ground CBA particles.

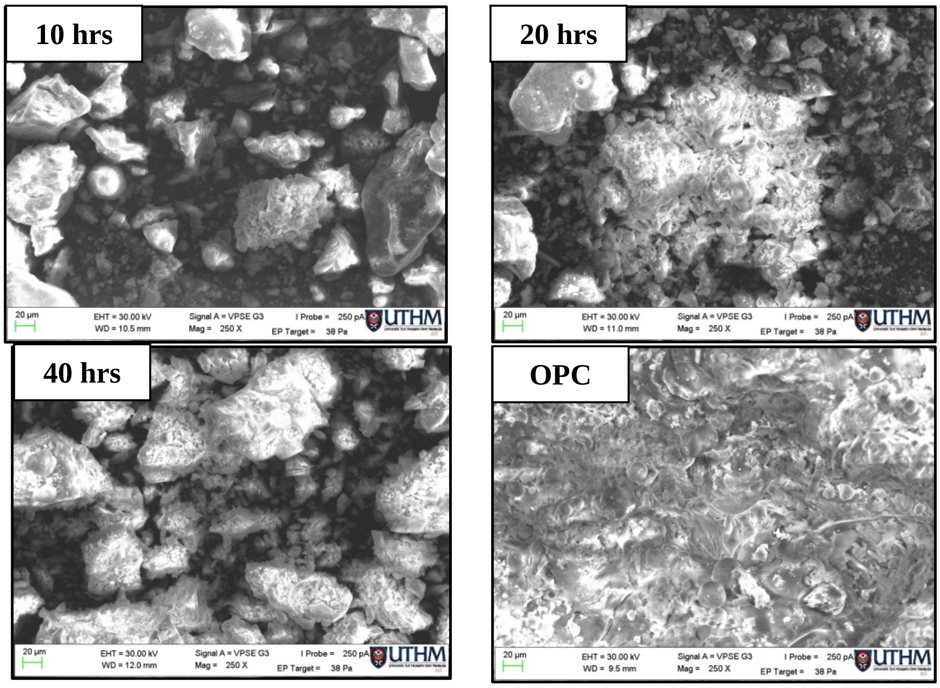

Figure 9 Scanning electron microscope images of CBA10, 20 and 40hrs and OPC.

The scanning electron microscope (SEM) images of OPC and CBA obtained through 20 and 40hrs. grinding process were scrutinized and found that particles sizes are very fine in appearance, but still sharp and irregular shape as compared to the ordinary portland cement (OPC). The observations based on the appearance of ground CBA is angular and rough in texture. This is influenced by the shape of crystal lite (C_3S) and anamartinez (C_2S) in the bottom ash. The ash particles mainly have an angular shape and porous nature. Whereas, numerous fine particles around the larger particles can also be observed in the SEM images, which have the appearance of metallic luster and could be the chances of metals present in the CBA [26].

4 Conclusion

The chemical characteristics of ground CBA exhibited that it can be classified as class-F ash. Therefore, it is expected that the use of ground CBA will leads to good strength performances in concrete, because of it's physical, chemical and microstructural properties. Whereas, fine particles of CBA will act as filling agent and increases the pozzolanic reaction inside the concrete / mortar. This study projected that ground CBA could be utilized as partial cement replacement material in concrete or mortar with relatively high strength and low porosity. Hence, ground CBA has a good potential to develop into a pozzolanic material.

In addition to that the following conclusions can be drawn from this study;

1. The grinding process significantly effects on physical properties of CBA. The specific surface area of the ground CBA was increased as the grinding period increased. Chemical properties revealed that the SiO_2/Al_2O_3 ratio for ground CBA is about 3, It is accountable for the higher value of strength. Therefore, it can be predicted the batter performance in the concrete in terms of strength gains. The silica modulus for ground CBA was also observed within the required range.
2. It was also empirically predicted that ground CBA has a good potentiality to mitigate the alkali silica reaction (ASR) in concrete. The consistency of cement paste increases with addition of ground CBA, because it absorbed more water than the normal cement.
3. Initial and final setting time of cement incorporating ground CBA was found to be higher than the ordinary cement paste. Almost similar values were observed with 10% cement replacement with CBA obtained through 10, 20 and 40hrs. Hence, future studies are required to investigate the strength and durability performances of a concrete containing ground CBA as partial replacement of cement.

Acknowledgement

The authors gratefully acknowledge the financial support of Research Management Centre (RMC), Universiti Tun Hussein Onn Malaysia, Malaysia through grant Vot No. U838 and the support of Mehran University of Engineering & Technology, Jamshoro, Pakistan is also acknowledged

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