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# EFFECTS OF FINE PARTICLE SIZE ON THE CHARACTERISTICS OF COAL BOTTOM ASH AS AN ENVIRONMENTALLY FRIENDLY MATERIAL IN CONCRETE PRODUCTION

In the current era, concern about the responsible disposal of industrial waste and its reuse has increased in all societies from the industry. Therefore, the researchers' institution is focusing its efforts on developing more environmentally friendly products from recycled waste, particularly in the area of sustainable construction. For instance, one of recycled waste is Coal Bottom Ash (CBA), a by-product of coal combustion that is produced in large quantities from thermal power plants. The aims of this study to investigate the physical, chemical and element characteristics of CBA obtained from thermal power plant in Malaysia. Also, CBA compared with cement characteristics to be used as cement replacement in the concrete mixture. Therefore, numerous tests have been performed to investigate CBA's physical and chemical characteristics. For physical properties such as specific gravity, particle size analysis, fineness modulus, bulk density and loss on ignition. For chemical properties such as X-ray fluorescence (XRF), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR) and thermogravimetric analysis (TGA) in an effort to obtain sustainable materials from thermal power plant waste. Based on the findings in this study, it can be concluded that CBA can be utilized as cement substitute in the production of concrete mixtures.

*Keyword:* Coal Bottom Ash; Cement; Concrete Production; Physical Characteristics; Chemical Characteristics; High Fineness

## 1. Introduction

Sustainability is well-liked in construction projects, especially in urban regions. In the 1990s, sustainable development became prevalent in construction, and related assessment standards were incorporated into the building sector. In addition, sustainable development is defined as an advancement that meets present needs without compromising the ability of future generations to achieve their goals [1,2]. The three main components of environmental sustainability are the economic community, the ecological community, and the social community [3,4]. As the construction sector expands, so does the need for environmentally friendly products. Therefore, faced with the need for performance changes, building designers are attempting to develop new design approaches by incorporating environmental considerations [5,6]. Sustainable construction is one of the most important phases of a construction project, as it is one of the very first phases of the construction process. The three R's rule that are effective components of sustainable building, reduce, reuse and recycle, are one of the most important components of environmental sustainability [7,8]. Nevertheless, economic growth and population growth create significant demand for electricity generation. Coal is the second largest energy source, contributes 30% of global primary energy consumption and is expected to remain the primary source of electricity generation in the future [9,10]. Coal combustion could also generate a number of hazardous wastes and has become a global concern due to its rapidly growing volume and negative impact on soil, the environment, and groundwater habitats [11,12]. Moreover, Sustainable management of coal combustion waste is critical to achieving the Sustainable Development Goals (SDGs), as SDG aims to "ensure sustainable consumption and production patterns" by achieving sustainable management and use of natural resources by 2030 and significantly reducing waste generation through waste prevention, reduction, and recycling [13-15]. As a result, a variety of novel and inventive recycling methods have emerged due to the fact that industrial byproducts generated in various sectors are considered resources rather than wastes

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Fig. 1. (a) Fresh CBA disposed to open area at thermal power plant (b) Collected CBA used in this study

disposed to landfill [16,17]. Over the last decade, numerous forms of industrial and agricultural waste have been incorporated into many types of concrete to minimize their negative environmental risks and costs [18,19]. Coal bottom ash (CBA) is one of those potential industrial wastes that are available in large quantities worldwide, which could be utilized as supplementary cementitious material in concrete production [20,21]. CBA is one of the byproducts produced by coal-fired energy plants, as illustrated in the Fig. 1.

Consequently, numerous studies [22,23] have been conducted on the physical characteristics and chemical composition of CBA. In the same vein, according to several previous studies [24,25] was reported that the physical characteristics of CBA was found are irregular and range from fine gravel to fine particles, which is suitable to be utilized as aggregate or cement depends in the size. While, available previous studies [26,27] was described the chemical composition of CBA as pozzolanic materials its content of silica, alumina, and iron oxid. Furthermore, in accordance with the standards ASTM C618 [28] was classified CBA to be considered as a pozzolanic materials with sum of $A1_2O_3 + SiO_2 + Fe_2O_3$ should be higher than 70%. Moreover, based on the evidence of ASTM C618 [28] standard, which can categorized CBA as pozzolanic materials class F or class C. However, the available several previous studies [29,30] on the use of CBA as alternative for cement, aggregate in the concrete mixtures. Some evaluations describe its influence on the properties of conventional concrete, mortar and other specific concretes. Accordingly, the development of concrete products containing this substance as one of the main ingredients in the concrete mixture would save landfill space, period, cost and energy for the disposal of this waste. This technique would minimize production costs and save the environment from the harmful effects of pollution [31]. Therefore, the present experimental work examined the physical characteristics and chemical composition of CBA to be use as alternative for cement in the concrete mixture. Moreover, this study investigated the influence of CBA in the microstructure properties, element analysis and chemical analysis.

## 2. Materials and methods

### 2.1. Sources of Coal Bottom Ash and Preparation

In this study, CBA was collected from Tanjung Bin thermal power plant located in Johor state, Malaysia. Also, this experimental work was used Ordinary Portland cement (OPC) CEM I 52.5 in accordance with Malaysian Standard MS 522 specification and EN 197-1. This study investigated the characteristics of original CBA and ground CBA in comparison with cement to be used as cement replacement in concrete mixture. The size for original CBA, and ground CBA particles was used as show in Fig. 2.

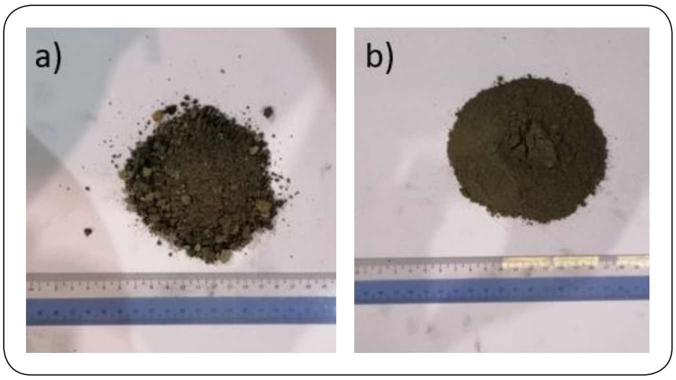


Fig. 2. Particles size of a) original CBA b) ground CBA

The CBA were dried in the electric oven at 105°C for 24 hours to avoid that from any moisture. The next step was sieve CBA at 300 μm to remove coarse particles. Next step the original CBA was placed into Los Angeles machine until get the required fineness. The size of steel ball was used is 50 mm and the number of steel balls was 20. Afterward, the ground CBA was sieved in order to reach a residue less than 35% in sieve 45 μm in accordance with ASTM C618 [28], and this study classified as class F ash type. The CBA was screened to remove the oversized particles to be more fineness and used as cement replacement.

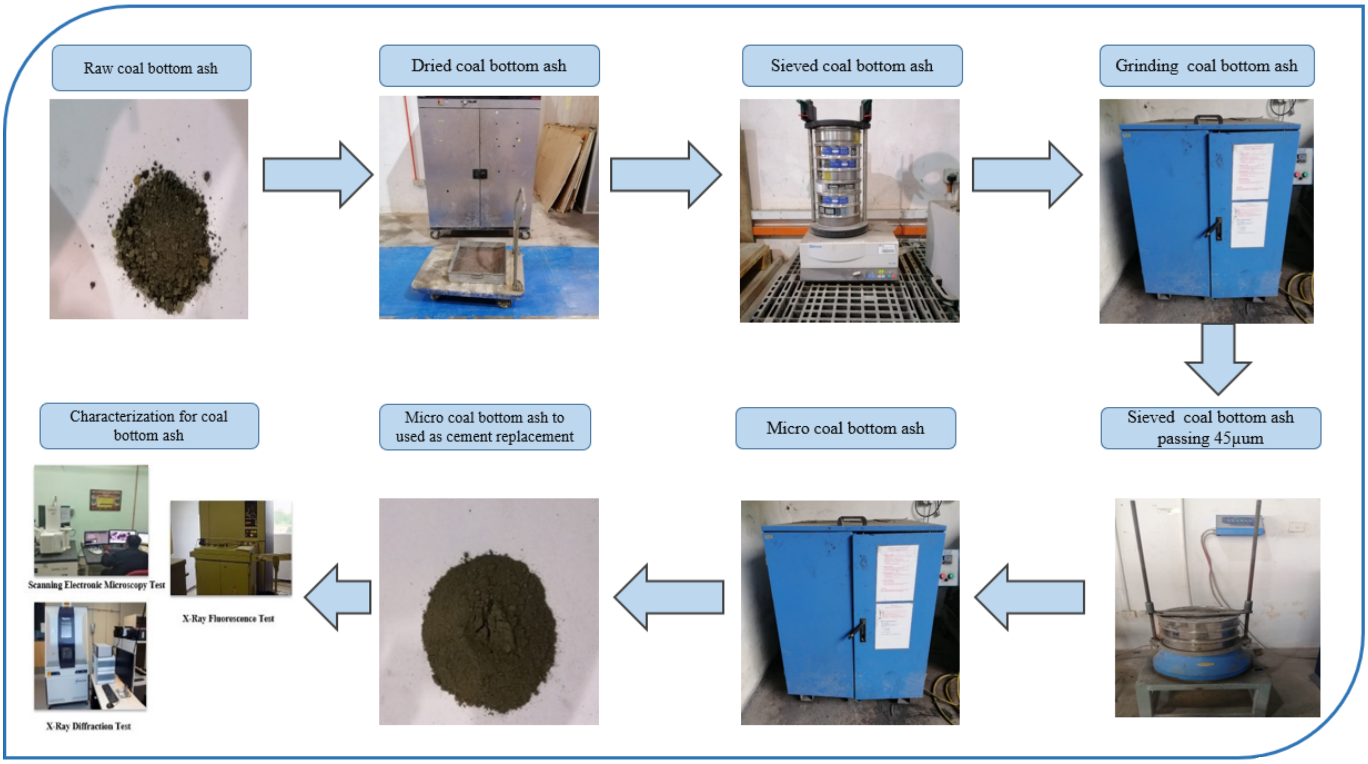


Fig. 3. Preparation process of CBA

The original CBA and ground CBA have average particles size rages less than 4.75 to passing sieve less than 45 µm respectively. The particles size of CBA can be reduced by increasing the grinding duration. The process of mechanical treatment to get micro fine particles for ground CBA as shown in Fig. 3.

### 2.2. Characterization Method of Coal Bottom Ash

The physical properties of CBA depending in the several factor such as investigation of the physical properties of CBA were carried out such as specific gravity, particle size analysis, fineness modulus, bulk density, and loss of ignition in accordance with specific standards and appropriate devices. For particle size analysis was used (Particle Size Analyzer machine) in order to perform the range size of CBA and cement particles. The specific gravity of CBA was examined according to the following procedures proposed standard ASTM C-29[32]. The fineness modulus of CBA was evaluated according to producer mentioned in ASTM C127 [33]. The chemical compositions of element analysis of CBA was evaluated using X-Ray Fluorescence (XRF) Analysis. The process for the analysis was take approximately 10 g of CBA and put it in the machine (Rigaku / ZSX Primus II). For the X-Ray Diffraction (XRD) was used to determine the mineralogical characteristics based in on its crystal morphology and compound in the CBA. The diffraction pattern generated was contrasted to the pattern that served as a benchmark, and the composition of the sample was calculated based on the position of the peaks that appeared. The diffraction angle of the device was set 5° to 80°. For the Scanning Electron Microscopy (SEM) was used to determine the elemental and morphological compositions of the CBA samples. The SEM was operated on to aluminum stubs by using adhesive carbon tape and is followed by gold coating to increase conductivity to prevent and then take a scanning electron microscope image. The stub was then placed into the vacuum chamber of the instrument and analyzed the surface morphology in magnification ranging from 100×-15000× times magnification. The Fourier Transform Infrared Spectrometer (FTIR) model of the device used in this study is the VERTEX 80. The characteristic of FTIR test is to conduct non-destructive analysis of samples to study the composition structure and chemical bond types of molecules. It can measure the bond length of molecules, guess the three-dimensional configuration of molecules, and determine the composition of organic functional groups in samples. The thermal property of the original CBA, the ground CBA, and the cement were determined using a Mettler Thermogravimetric (TGA) instrument. At a heating rate of 10°C/min, the TGA heated the specimens from room temperature to 1000°C.

## 3. Result and discussion

### 3.1. Physical Properties of Coal Bottom Ash

In this study the influence of the physical properties of CBA and cement were evaluated using advanced instrument to observe the smaller particles size. The machine was used for particles size analyzer (Malvern Hydro 2000MU) as shown in the Fig. 4. The (Malvern Hydro 2000MU) instrument can detect particle sizes between 0.05 and 2000 μm. For the instance four sample of CBA with different grinding periods. The finding of the specific gravity for original CBA and ground CBA was found to be 2.21, and 2.37 respectively, which is lower than specific gravity for cement. This is due to the pore structure of the particles of CBA, as well as its low specific gravity, which makes it susceptible to degradation under load or compaction. According to several previous [34-36] studies was observed the specific gravity for CBA in the range of 1.99 to 2.50, which is different from thermal power plant and the grading duration and type of coal used. Beside that the Surface Area for original CBA, ground CBA and cement were found as 0.179, 0.494, and 0.867, respectively. While the findings of ground CBA and cement were compared, the properties were found to be equivalent, making it a potential cement alternative for further investigation. In particular, the fineness and particle surface area of CBA increased with increasing grinding time.

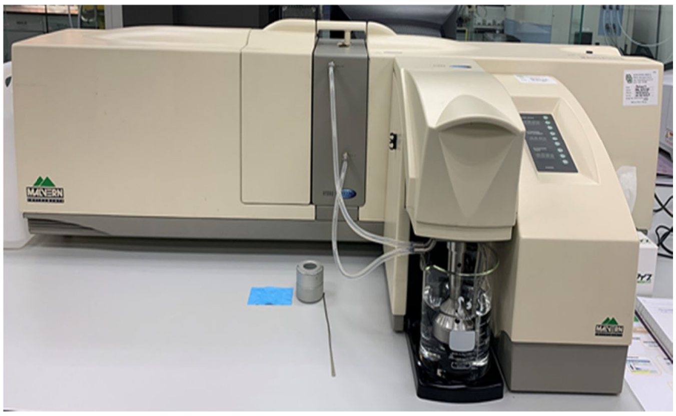

Fig. 4. Particle Size instrument (Malvern Hydro 2000MU)

The particle size of original CBA, ground CBA and cement were determined through particle size analyzers model called (Malvern Hydro 2000MU), which shows the physical properties of, original CBA, ground CBA and cement such as range of particle sizes, specific gravity and results are provided in TABLE 1. Furthermore, the color of CBA was observed in this study to be gray after grinding was found to be darker in color as dark gray or Blackish as illustrated in TABLE 1. Generally the CBA was well graded and the range of particle size was comparable as cement, the results of range of particle size as shown in the TABLE 1. Whereas, according to study by Mangi et al. [37] was observed that the particles size for ground CBA less than 45 μm and the color of CBA was from gray to dark gray after grinding period.

### 3.2. Chemical composition of Coal Bottom Ash

The major components of ash content directly affect the chemical composition of CBA. While different category standards could be established in the regions for each coal class, ASTM D388-18a (2018) and ASTM D4326-13 (2013) [38,39] regulate the essential constituents of coal. The X-ray Fluorescence (XRF) was used in order to obtain the chemical composition of CBA. Analyses were performed on CBA samples collected from Tanjung Bin thermal power plant. The chemical composition results of the original CBA, ground CBA, and cement are shown in the TABLE 2. The results show that the main chemical compounds such as silicates ($SiO_3$), aluminates ($Al_2O_3$), and iron oxide ($Fe_2O_3$) were detected as major components by X-ray fluorescence (XRF), as well as a variety of other chemicals in lower proportions. The chemical composition of the original CBA was classified as class C pozzolanic material. After grinding the CBA, the ground CBA was classified as category F pozzolanic material according to ASTM C618 [28] as shown in TABLE 2. Since the total sum of $SiO_3$, $Al_2O_3$ and $Fe_2O_3$ of ground CBA is more than 70%. The total sum of silica, alumina and iron is the most important indication of the pozzolanic properties of the material. Similar result has been reported by Mangi et al. [29] was found the ground CBA after grinding achieve the pozzolanic properties in accordance with ASTM C 618 [28]. Moreover, previous [40,41] studies have shown that when the average particle size of CBA is less than 10 micrometers, fineness plays a greater role in inhibiting ASR mitigation. Consequently, it has been shown that $SiO_2/Al_2O$ (SA) ratios with compositions in the range up to 3.9 exhibit higher strength [42,43]. While changes in SA ratio above this range are associated with weak strength for the structural element. Therefore, the original CBA and the ground CBA were evaluated based on the elemental composition of the oxides for the samples as shown in the Eqs. (1)-(3) below. The results show that the SA ratios for the original CBA and the ground CBA as 2.6, 3.8 respectively, which is the range as reported in the previous studies.

$$\text{SA ratios} = \frac{SiO_2}{Al_2O_3} \tag{1}$$

$$\text{SA ratios for original CBA} = \frac{37.2}{13.8} = 2.6 \tag{2}$$

$$\text{SA ratios for ground CBA} = \frac{50.9}{13.3} = 3.8 \tag{3}$$

TABLE 1

Physical properties of cement and CBA

| Sample ID | Specific gravity | Bulk Density g/cm$^3$ | Range of Particle Size (Micron) | | | Surface Area (m2/g) | Color |
|---|---|---|---|---|---|---|---|
| | | | D10 | D50 | D90 | | |
| Cement | 3.15 | 1.44 | 3.753 | 20.689 | 52.420 | 0.867 | Grey |
| Original CBA | 2.21 | 1.27 | 22.857 | 130.820 | 391.875 | 0.179 | Gray |
| Ground CBA | 2.37 | 1.38 | 5.970 | 64.683 | 357.448 | 0.494 | Blackish or dark gray |

TABLE 2

Chemical composition of cement, original CBA, and ground CBA

| Chemical elements (%) | Cement | Original CBA | Ground CBA | Class of pozzolanic materials ASTM C-618 | | |
|---|---|---|---|---|---|---|
| | | | | Class N | Class F | Class C |
| Silicon Dioxide ($SiO_2$) | 14.4 | 37.2 | 50.9 | Minimum 70% | Minimum 70% | Minimum 50% |
| Aluminium Oxide ($Al_2O_3$) | 3.55 | 13.8 | 13.3 | | | |
| Ferric Oxide ($Fe_2O_3$) | 3.10 | 7.82 | 17.3 | | | |
| Sulphur Trioxide ($SO_3$) | 3.17 | 0.420 | 0.534 | Maximum 4% | Maximum 5% | Maximum 5% |
| Calcium Oxide (CaO) | 63.8 | 7.00 | 11.2 | — | — | — |
| Magnesium oxide (MgO) | 0.693 | 2.06 | 1.52 | Maximum 4.0% | Maximum 5.0% | Maximum 5.0% |
| Potassium Oxide ($K_2O$) | 0.818 | 0.799 | 2.07 | — | — | — |
| Titanium Dioxide ($TiO_2$) | 0.228 | 0.797 | 1.32 | — | — | — |
| Phosphorus pentoxide ($P_2O_5$) | 0.0485 | 0.130 | 1.31 | — | — | — |
| $SiO_2$+$Al_2O_3$+$Fe_2O_3$ | 21.05 | 58.82 | 81.5 | — | — | — |
| Loss on ignition | 2.75 | 3.40 | 4.15 | — | — | — |

### 3.3. Morphological Characterization of Coal Bottom Ash and Cement

The morphology characteristics of the original CBA, ground CBA, and cement was characterized by scanning electron microscopy examination (SEM), as illustrated in the Fig. 5. Furthermore, the SEM test assists in analyzing the sample's structure and shape. The SEM investigation and study of the morphological properties of solid objects includes the characterization of nano and micro particles. Through morphology investigation, it was observed from the SEM image of the original CBA, and ground CBA that the particles had a porous, irregular, and sharp shape, as illustrated in Fig. 5. This showed that voids were present. Based on the shape and porous particles of CBA, it was expected that the CBA higher water absorption compared to cement. The cement particles were tiny, angular particles, while the original CBA and ground CBA particles were larger, visually more porous, and had a disordered shape. Apart from that, similar results on the SEM images of CBA have been reported in previous research [44,45]. Furthermore, the size of the particles of original CBA can range from 300 micrometres to a few micrometres in certain cases. Moreover, for the ground CBA the particles size was less than 45 µm, which is in accordance with ASTM C618. From the Fig. 5 was observed that finer particles that have greater density and give the impression of a metallic.

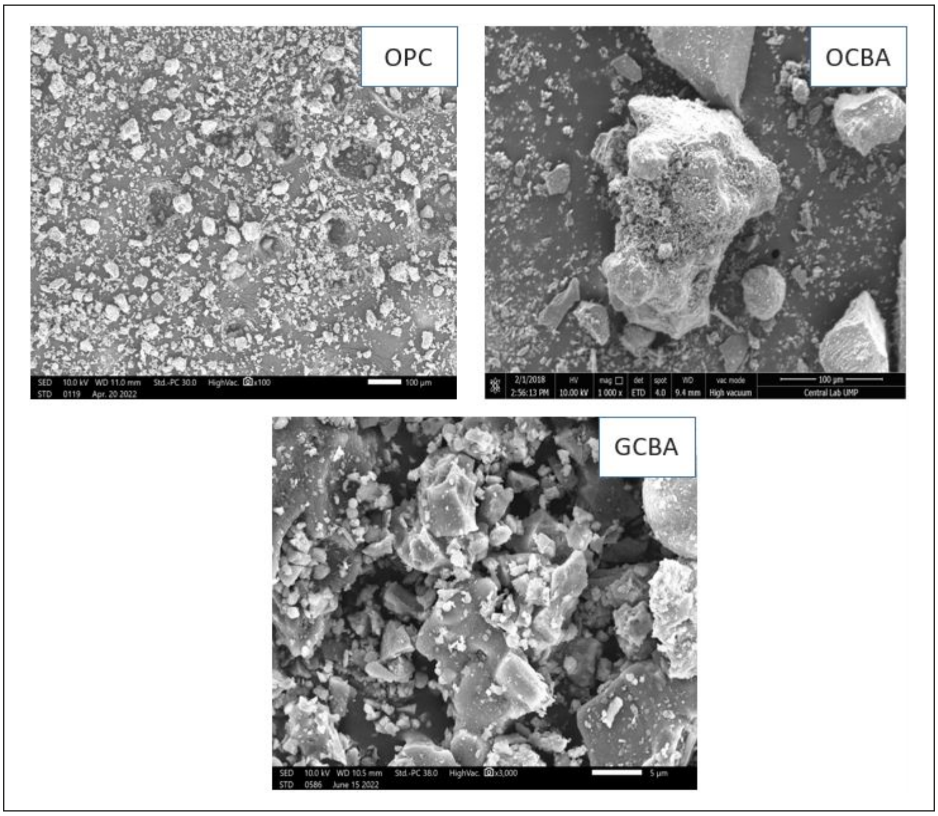


Fig. 5. Scanning electron microscope images for cement, original CBA, ground CBA

### 3.4. Chemical Analysis of Coal Bottom Ash using X-Ray Diffraction (XRD)

The x-ray diffraction was utilized to investigate the different phases present in the original CBA, the ground CBA, and cement. The powder specimens for X-ray diffraction examination were produced. Fig. 6. depicts an XRD diffraction pattern with a succession of peaks that correlate to certain planes in the mineral crystalline phase of original CBA and ground CBA samples. The XRD of CBA formed silica is in perfect accordance with a number of prior results which reveal that peaks demonstrate the existence of silicon dioxide [46,47]. According to the Fig. 6 of the XRD findings, the key components in CBA was found include such as quartz ($SiO_2$), mullite ($Al_6Si_2O_{13}$), and iron oxide ($Fe_2O_3$). This finding was consistent with the findings of the chemical properties. The chemical evaluation conducted by the CBA demonstrated that these materials could be utilized as building alternatives. These patterns diffract X-Rays of a certain wavelengths at a specific angle, often represented in degrees. Consequently, the diffraction peaks of each crystal is unique and can be utilized to classify minerals or calculate component quantities. With a reduction in silicate crystallinity, amorphous material content develops, causing diffraction peaks to spread and vanish while backgrounds intensity rise. A considerable quantity of quartz ($SiO_2$) and mullite ($Al_6Si_2O_{13}$) was detected by XRD analysis in both the original and ground CBA specimens. CBA has been demonstrated to have a crystalline structure. Consisting of quartz, hematite, and mullite. The findings have further established the existence of $SiO_2$ and $Fe_2O_3$ phases in CBA using XRF test. In addition, the high crystallinity of each component is shown by a peaks structure that is tight and distinctive [48].

On the other hands, the formation of the cement consists of main chemical compound such as Silicate ($C_3S$), dicalcium silicate ($C_2S$), tricalcium aluminate ($C_3A$), and Tetracalcium aluminoferrite ($C_4AF$). Throughout every instance, the cement phases appeared to be highly crystallised, with the major calcium silicate phases ($C_3S$, $C_2S$) showing maximum at the values that correlate to 2θ. The strong correlation of significant peak intensity of all the major phases of cement components in the angular range of 30° to 35° for 2 values is one of the main obstacles experienced in the qualitative and quantitative evaluation of cement. This necessitates the identification of the individual elements extremely difficult. During the XRD investigation, it was determined that CBA has a reasonably straightforward physicochemical characteristics comprised of quartz, corundum, and hematite. Cement's specific gravity as determined by the picnometer procedure was 3.15. This low value indicated that hollow particles, such as agglomerates and plerospheres, could be present in considerable amounts in the CBA.

### 3.5. Chemical Analysis of Coal Bottom Ash using Fourier-Transform Infrared Spectroscopy (FTIR)

Another important analysis to provide evidence on the formation chemical structures of functional groups of OCBA,

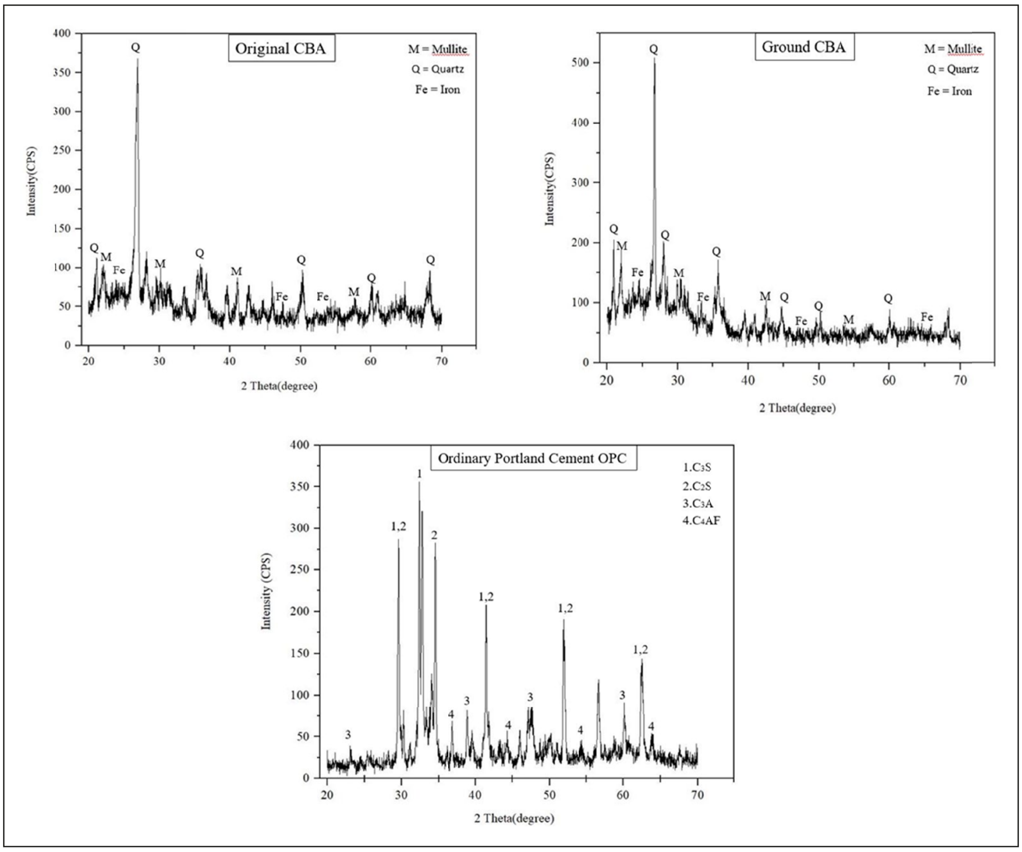


Fig. 6. X-ray diffraction (XRD) analysis for original CBA, ground CBA, and cement

GCBA, and cement networks were further analyzed by Fourier Transform Infrared Spectroscopy (FTIR) analysis for all the specimens. Fig. 7 displays the FTIR spectra for OCBA, GCBA, and cement fractions. Moreover, the results showed that the peaks of FTIR are almost the same. The most characteristics band or the most peak value is located in the range of 500 cm$^{-1}$ to 1000 cm$^{-1}$, which is due to two reasons. First reason the Si–O–Si bending mode for OCBA, and GCBA due to high percentage of silica compared to cement. Also, Si–O–Si for GCBA position is shifted to the right position or lower frequency compared with the OCBA, implying a chemical change and different particles size. The second reason is due to lager particle size for the OCBA, and GCBA compared to cement particles. Overall, the CBA was observed that high waves number indicate that higher absorbed moisture as collected from their sources, which indicates that the main components of CBA particles are $SiO_2$ and $Al_2O_3$.

On the other hand, the waves for the cement at 1000 cm$^{-1}$ started stretching are observed. From the FTIR Fig. 7 for the cement was found that the peaks above 1000 cm$^{-1}$ become more to straight line and the waves was reduced. This is due to the presence of quartz in cement. Nevertheless, FTIR for cement at the range of 2000 cm$^{-1}$ to 4000 cm$^{-1}$ is mostly due to the present of $C_3S$, $C_2S$, and $C_4AF$ in the compounds of the cement particles. This finding in the agreement of the previous studies by Danchuwa et al. and Shrestha et al. [49,50].

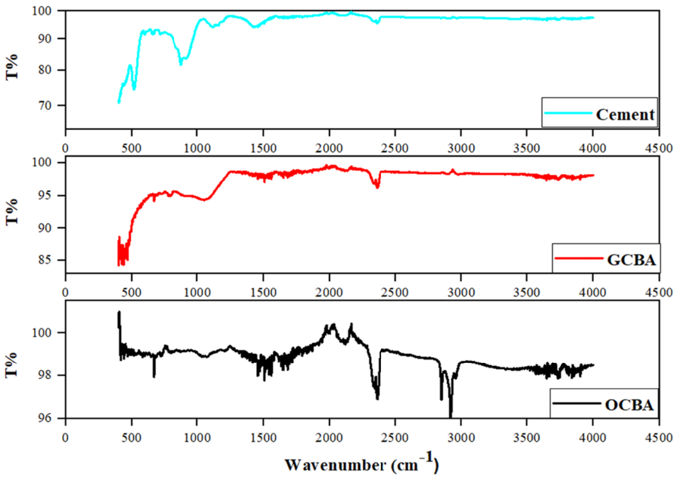


Fig. 7. Fourier-Transform Infrared Spectroscopy (FTIR) analysis for original CBA, ground CBA, and cement

### 3.6. Chemical Analysis of Coal Bottom Ash using Thermogravimetric analysis (TGA)

This technique permitted continuous weighing of the sample as a function of temperature at a desired temperature from room temperature (28°C) to 1000°C using the device (TGA Q500). The thermal gravimetric analysis (TGA) of the cement, original CBA, and ground CBA are shown in Fig. 8. For the cement the total weight losses around 5.0 wt% corresponds to the weight loss due to the evaporation of surface adsorbed water [51]. The adsorbed water was extracted by cement from the atmospheric air while it was kept in storage. For the original CBA the total weight loss around 16 wt% corresponds to the water loss physically adsorbed or contained inside the pore structure in the case

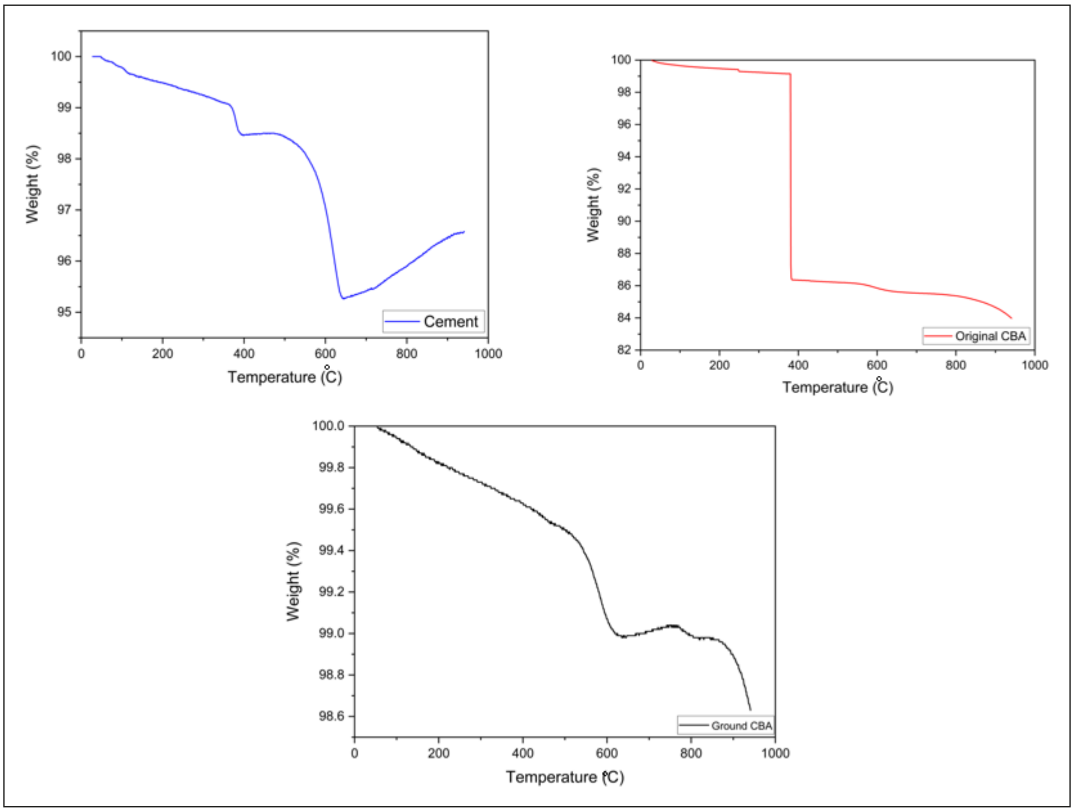


Fig. 8. Thermogravimetric (TGA) analysis for Cement, Original CBA, and Ground CBA

of original CBA. The curve of original CBA showed three major weight losses at room temperature 28°C to 200°C, and 200°C to 400C, and 400°C to 1000°C. For the ground CBA the total weight loss of around 2% corresponds to the moisture absorbed during preparation and grinding process of ground CBA. The curve of ground CBA gradual weight loss from room temperature (28°C) to 400°C because of absorbed moisture during grinding process which is oven dried before starting the grinding process. A major weight loss is observed from 400°C to 750°C attributed to oxidation and burning of the organic particles entrapped inside the ground CBA. From 750°C onward weight loss is reduced although it continues to decrease up to 1000°C and beyond. Consequently, TGA of ground CBA showed different thermal behavior compared to cement, original CBA. This is due to the original CBA presence of excess of water; absorbed during cooling with water at power plant [52]. Furthermore, for cement contain surface moisture particles due to storage process. Overall, the main weight loss for CBA is due to the removal of moisture from the samples. Moreover, the weight loss of CBA at a higher temperature after burning carbon is very low. This showed that CBA was thermally stable and can be used in thermal applications. Apart from that, his finding in the agreement of the previous studies by Hashemi et al., and Phutthananon et al. [53,54].

## 4. Conclusion

The use of CBA as a building material requires an investigation of its engineering properties and environmental variables. Consequently, this study examined the influence of CBA to be used as construction materials in terms of physical, chemical and microstructural properties produced from thermal power plants. Based on the present investigation, these points can be concluded:

- The use of CBA as a supplementary cementitious material could minimize energy consumption and $CO_2$ emissions associated with cement production, as well as the amount of CBA disposed in landfills.
- The particle size analysis revealed that the CBA particles had diverse porosity textures, and irregular shapes.
- The XRD analysis indicated that the CBA samples consisted primarily of quartz ($SiO_2$), mullite ($3Al_2O_3 \cdot 2SiO_2$) and iron ($Fe_2O_3$). Furthermore, the cement sample consisted primarily compounds of tricalcium Silicate ($C_3S$), dicalcium silicate ($C_2S$), tricalcium aluminate ($C_3A$), and Tetracalcium aluminoferrite ($C_4AF$). According to the XRF analysis, the CBA specimens are categorized as class F. Consequently, they could be utilized as a potential ingredient with or without the addition of suitable additives, such as fly ash or silica fume.
- The FTIR spectral analysis indicated that the CBA samples have main functional bond Si–O–Si due to high amount of silica. Furthermore, the main functional bond for cement contain Si-O, which makes the CBA suitable materials to be used as partial cement replacement.
- Encourage disposal of obsolete CBA from landfills and surface impoundments. Local governments could implement a recycling system to minimize CBA dumping and reduce environmental impact. The use of CBA as a substitute building material could help solve certain environmental challenges. Sustainable concrete could be produced by substituting CBA for fine aggregate and cement. However, due to the nature of coal and the variety of combustion processes, the same studies must be conducted in many power plants to show that CBA could be utilized as a substitute for building materials.

## Recommendations for Future

Based on the findings of this research, there is the gaps need to be addressed. Therefore, it is recommended that further studies concentrate on the following areas:

- Feasibility and comparative analysis of the economic and environmental benefits of using CBA as a substitute for cement in the fast-growing concrete production should be investigated.
- It is an application that will eliminate CBA treatment and dumping in an open landfill.
- Its incorporation in concrete as an alternative to cement can significantly mitigate environmental problems of global warming associated with cement production.
- In order to utilize the GCBA as a supplementary cementitious material as an environmentally friendly material in concrete production, it would be necessary to develop material processing technologies for CBA ashes before they are used in concrete production. For example, appropriate treatment of CBA ashes (e.g. chemical pretreatment, mechanical pretreatment) can eliminate the hazardous content, so that the adverse effects on concrete can be reduced.

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