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Characterization of Coal Combustion Products from Malaysian Power Plant for Building Materials Applications

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Abstract. Coal combustion by Products (CCPs) are produced during coal combustion in the process of electric generation. Without proper handling system, this will cause serious problems towards human and environmental. Nevertheless, with proper treatment, these ashes are applicable in many areas specially building construction materials. Coal Bottom Ash, Coal Fly Ash and Cenosphere are three main wastes produced from power plant. The aim of this study is to determine the characteristics of samples collected from different parts of Malaysia Power Plant. Characterization testing involved included surface morphology, chemical composition (oxides), chemical components, amorphousness, and particle size distribution testing. From this study, CBA have more angular-shaped particles compared to CFA which is smoother surface morphology. However, Cenosphere shown the most uniform and spherical shaped particles. EDS testing shown Existing CBA have highest Carbon content (46%) while Cenosphere is lowest (11.38%). The percentage oxides contents for all samples demonstrate more than 70% of Total $SiO_2 + Al_2O_3 + Fe_2O_3$. Hence, all ashes considered as Class F (pozzolanic). CBA, SFA, CFA and cenosphere has significantly more amorphous phases of silica and alumina, and this will increase the concrete strength. Due to agglomeration of ashes on ash pond, the cumulative PSDs results shown that the particle size of the existing sample obtained larger than the new sample. Minimum particles size of SFA (New - Dry) is 2 µm while SFA (Existing 2) is 20 µm. From characteristic determination above, it shown that each type of ashes has its own uniqueness and capability to be applied wide range of applications.

1 Introduction

In the search of sustainable materials to mitigate the effect of climatic change, it is critical for the construction industry to study the thermal performance characteristics and assess its performance of the construction materials as cost saving in energy consumption for various potential uses in the building industry[1] . A study conducted in Malaysia suggests that approximately 19% of the energy utilized across all sectors in the country originates from residential buildings within Malaysia. [2]. Coal is a main source to produce electricity and heat through combustion process. The burning of bituminous and sub-bituminous coal as well as lignite in thermal power plants to generate electricity results in the production of solid residues including fly ash, bottom ash, boiler slag, and flue gas desulphurization (FGD) materials. These materials, collectively referred to as coal combustion by-products (CCPs), constitute significant waste products, notably the substantial volume of fly ash generated continuously throughout the year at Coal Fired Power Plants.Fly ash is a by-product of coal combustion. Continuous ash production consequences in the expansion of ash dumps [3][4].

Fast-developing country like Malaysia with thriving economies and hence the demand of electricity is increasing. There are six thermal power plants operated in Malaysia with annual coal consumption of 24.7 million tonnes [5]. Due to the high demand of coal consumption, the production of coal and waste was increased. Tenaga Nasional Berhad (TNB) consumed 1.5 million tonnes of coal each year [6], it was reported that coal consumption is projected to steadily

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increase due to new coal-fired generating units. The annual coal consumption of power sector in peninsular Malaysia for 2016 was recorded as 29 million tonnes [7].

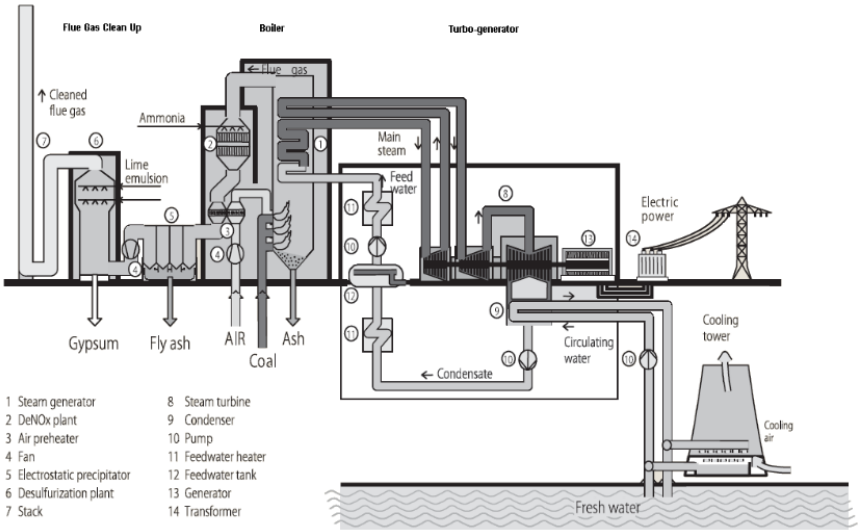

Figure 1 Typical Layout of Power Plant

As indicated in [8], the optimal replacement percentage for coarse aggregate in high-strength concrete is 10% boiler slag, suitable for offshore and road construction. Coal bottom ash (CBA) constitutes a portion of the non-combustible residue resulting from combustion processes in power plants, boilers, furnaces, or incinerators. Characterized by angular, irregular, and porous particles with a rough surface texture [9], CBA particle sizes range from fine gravel to fine sand, possessing interlocking characteristics. Research literature demonstrates that while the strength development pattern of bottom ash concrete resembles that of conventional concrete, there's a decrease in strength at all curing ages due to higher porosity and increased water demand [10]. This is corroborated by [11], which suggests that replacing coarse aggregate with CBA in the range of 25% to 100% reduces early-age strength but increases long-term strength by 56-65%. CBA concrete exhibits a slower initial strength development, reaching optimum strength at a faster rate beyond 28 days due to the pozzolanic action of CBA. Substituting OPC with CBA at percentages of 10 to 30% during mixing results in decreased workability compared to control mixtures [12].

Fly ash, the finest coal ash particle, earns its name from being transported from the combustion chamber by exhaust gases. It constitutes the fine powder formed from the mineral matter in coal, containing non-combustible coal matter and a small amount of residual carbon from incomplete combustion [13], [14]. Some studies suggest that replacing a portion of cement with fly ash and cenosphere during concrete production yields products with lower thermal conductivity and diffusivity. These applications demonstrate the wide potential of CCPs in various areas. High levels of low lime fly ash as a cement component in the concrete industry have been tested, with results indicating that up to 45% FA could be added with Portland cement, leading to a range of practical concrete strength designs, despite some reduction in early strength [15].

Cenosphere, extracted from fly ash, possesses unique properties including spherical shape, lightweight, heat resistance, enhanced insulation, thermal stability, and chemical inertness [16], [17], [18]. With particle sizes ranging from 5 to 500 µm and lower density compared to water (0.4–0.72 $g \cdot cm^{-3}$) and very low thermal conductivity (about 0.065 $W \cdot m^{-1} \cdot K^{-1}$), cenospheres find extensive use as construction materials [19]. Incorporating 20% cenosphere as sand replacement in concrete resulted in reduced compressive and tensile strengths, along with reduced density compared to other percentages [20], [21]. This study also indicated a decrease in the k value to as low as 0.62 W/m K due to cenosphere incorporation and mixtures [22]. Additionally, [22] noted that replacing 30% of sand with cenospheres significantly reduces the thermal conductivity of concrete, aligned with reductions in density and compressive strength, attributed to the spherical and porous properties of cenospheres.

Hence, the aim of this study is to explore the characteristics of Coal Bottom Ash (CBA), Coal Fly Ash (CFA) and Cenosphere in terms of surface morphology, chemical components, chemical composition, amorphousness, and particle size distribution.

2 Design of Experiment Set Up

2.1 Sample collection

Three different types of CCPs were collected from different parts of Malaysia Power Plant. Two fresh CBA samples were obtained from the combustion furnace and coal ash pond. CFA was collected from the silo hopper, and SFA was collected at the ash pond. The samples were packed in storage bags, loaded onto lorry with an enclosed cabin, then transported to the Scheduled Waste Storage at Civil Engineering Laboratory. Sample collection activities from different part of power plants were shown in Figure 2 below.

Figure 2 Sample Collection activities from power plant (a)CFA, (b)CBA and (c)Cenosphere

Generation and disposal of CCP from the KEV coal power plant into the ash pond are increasing. The generation volume of CBA is 80,000 metric tons per year, and CFA is 4000,000 metric tons per year (Refer to Figure 3 below).

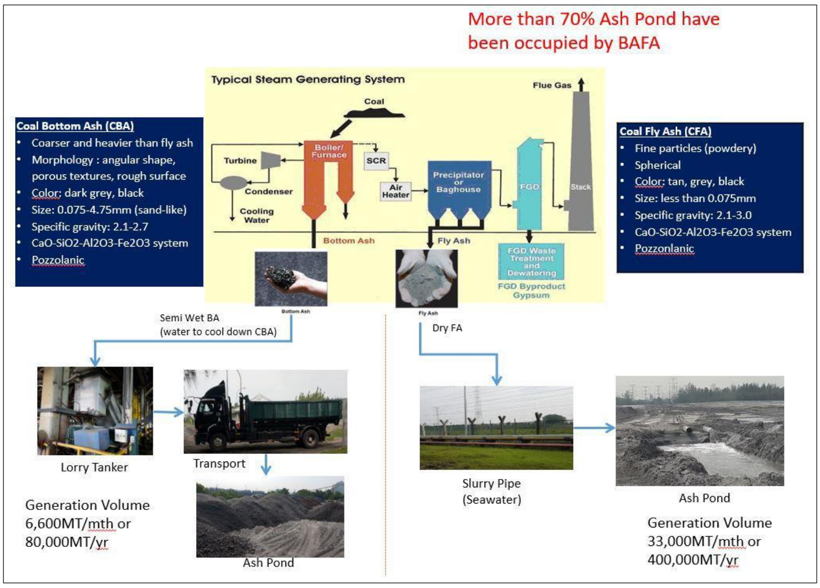

Figure 3 CBA and CFA generation process and volume.

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2.2 Material Characterization

Characterization study has been conducted to determine the ash characteristics and its suitability to be used as building materials. Coal combustion products (CCPs) have been collected from Malaysian Power Plant, stored in airtight container with clean and dry conditions before testing. Field Emission Scanning Electron Microscopy (FESEM) (Model : XHR Extreme High Resolution Field Emission Scanning Electron Microscope (XHR-FESEM) Model FEI Verios 460L**)** is a high-resolution microscopy technique that uses a beam of electrons to scan the surface of a sample and create a detailed image of surface morphology of ashes. Chemical components of ashes collected from power plant were evaluated using Energy-Dispersive X-ray Spectroscopy (EDS) Characterization. Next, chemical composition (oxides) and amorphousness were determined using X-ray fluorescence (XRF) and X-ray fluorescence (XRF) Characterization respectively. The last testing was conducted is Particle Size Distribution was carried out in accordance with ASTM 2007 to control the aggregate size.

Table 1 Different types of CBA, CFA and Cenosphere obtained from Malaysian Power Plant.

CCPs Collection from KEV	Ash Types
Coal Bottom Ash (CBA)	Existing New (Dry) New (Wet)
Coal Fly Ash (CFA)	New
Slurry Fly Ash (SFA)	Existing 1 Existing 2 New (Dry) New (Wet)
Cenosphere	Cenosphere

Figure 4: Physical appearance of ash samples.

3 Results and Discussion

3.1 Surface Morphology

The FESEM results obtained for 9 samples of ash are shown in Figure 4 -12. Each sample has two magnification, 1000x and 5000x magnification (Figure (a) and (b)), respectively. It was observed that both CBAs had largely angular-shaped particles, with a small fraction of spherical particles as per Figure 4,5 and 6.
Figures 7-10 represent the surface morphology for Slurry Fly Ash. It can be observed that the slurry fly ash had a smooth surface and a spherical morphology, and the particles were generally found as agglomerates. This characteristic give advantage in improving concrete workability as well as compact ability.

Figure 11 and 12 represents the surface morphology of cenosphere. Cenosphere is an ash extracted from fly ash. It normally found floating around the powerplant. It was observed that the cenosphere have a smooth surface with spherical morphology. This agrees with literature, where cenosphere was reported to have a hollow structure with a spherical shape [23], [24].

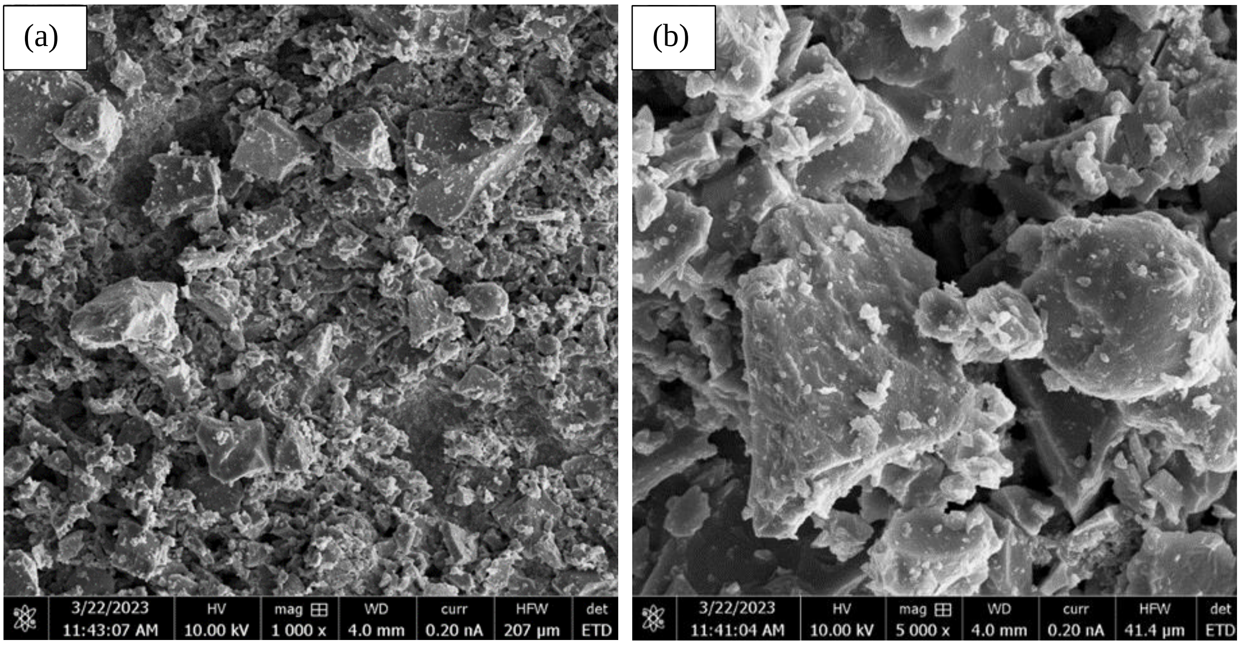


Figure 5: FESEM Image of CBA - Existing: (a) 1000x magnification and (b) 5000x magnification.

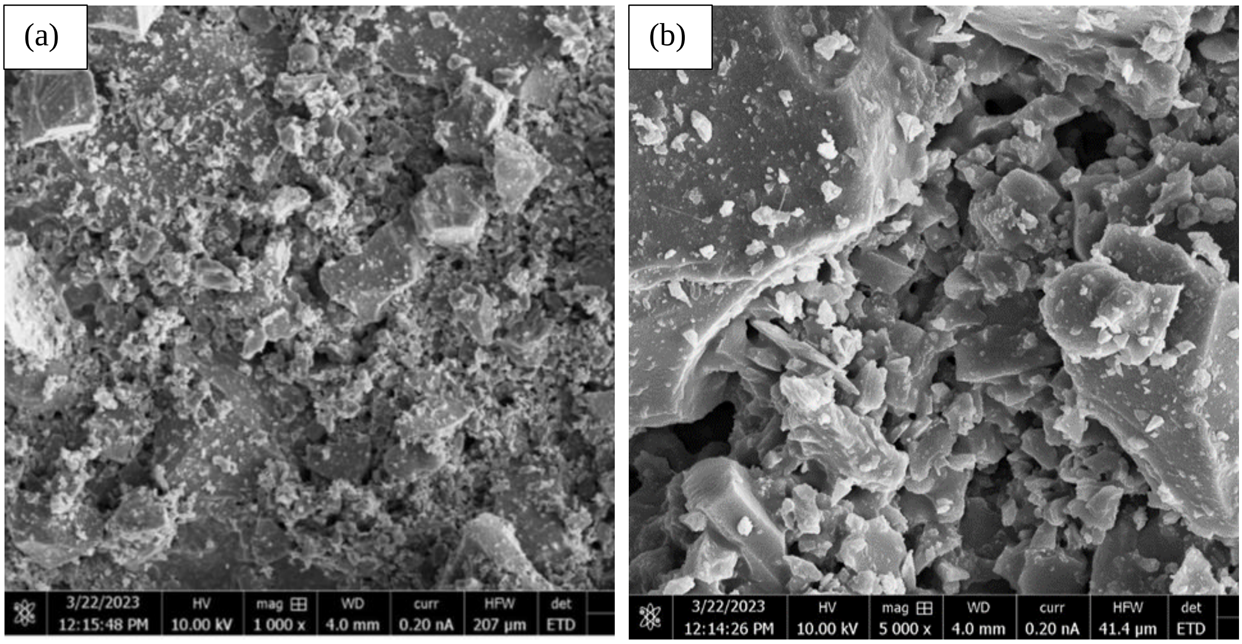


Figure 6: FESEM Image of CBA - New (Dry): (a) 1000x magnification and (b) 5000x magnification

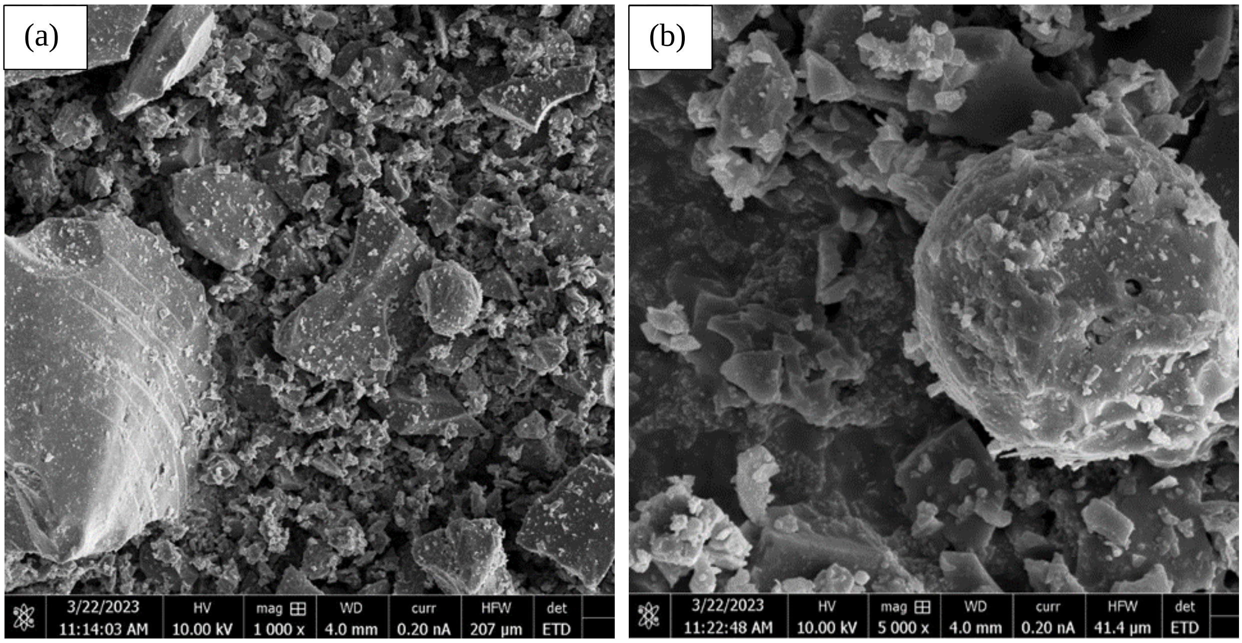


Figure 7: FESEM Image of CBA - New (Wet): (a) 1000x magnification and (b) 5000x magnification.

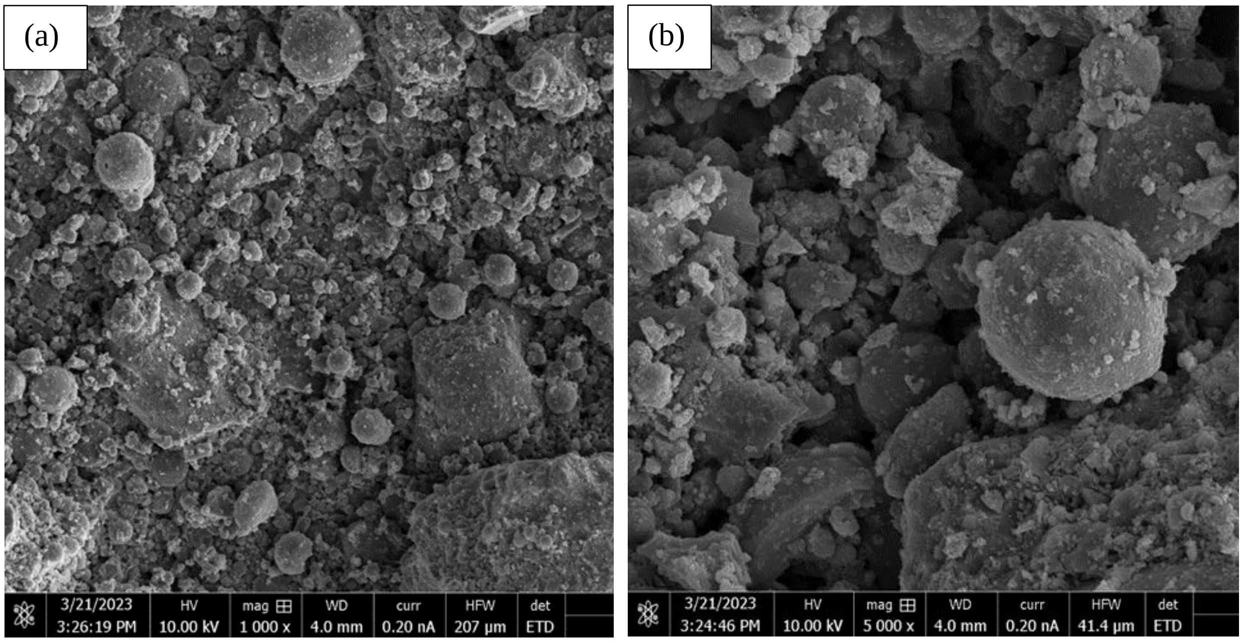


Figure 8: FESEM Image of SFA - Existing 1: (a) 1000x magnification and (b) 5000x magnification

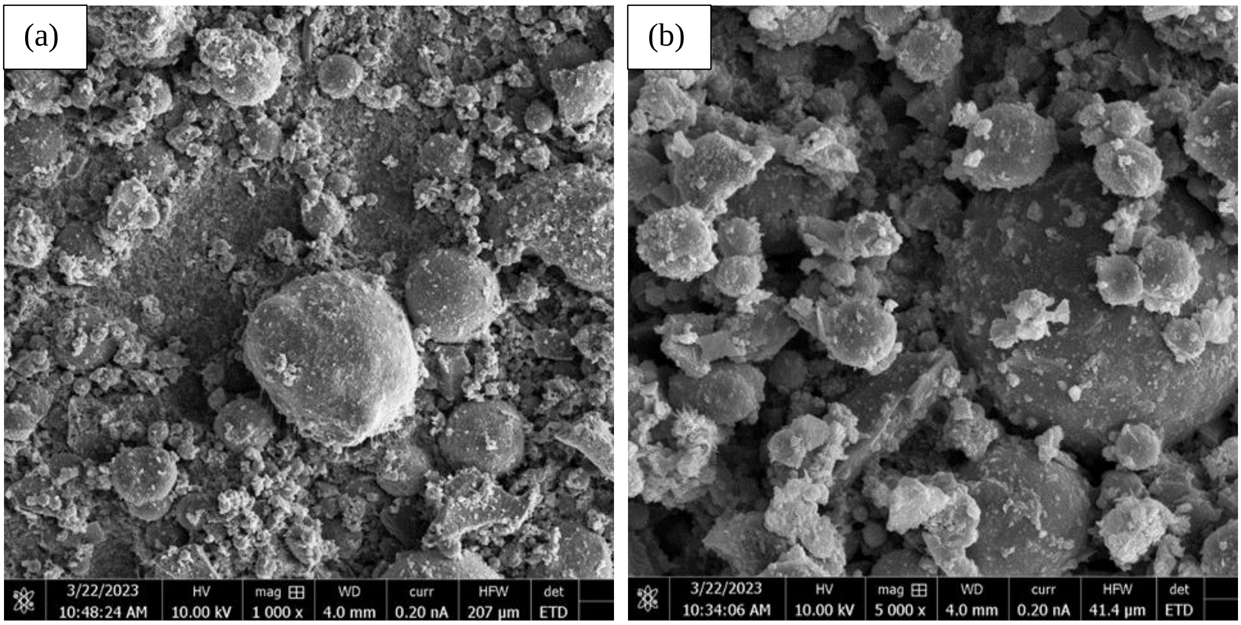


Figure 9: FESEM Image of SFA - New (Dry): (a) 1000x magnification and (b) 500

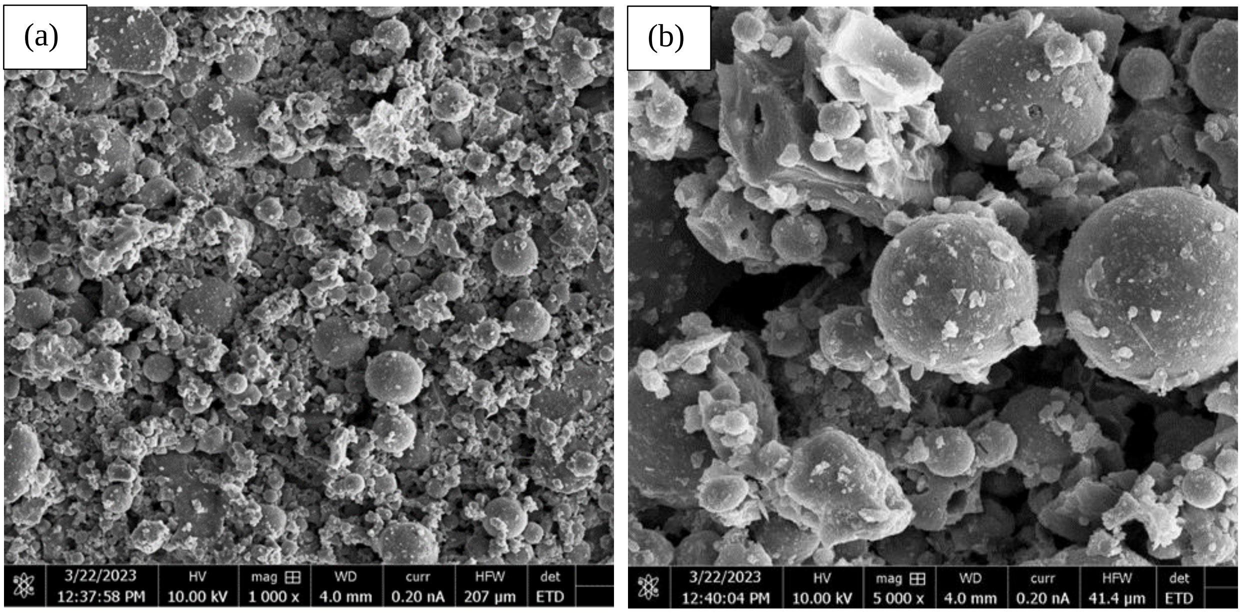


Figure 10: FESEM Image of SFA - New (Wet): (a) 1000x magnification and (b) 5000x magnification.

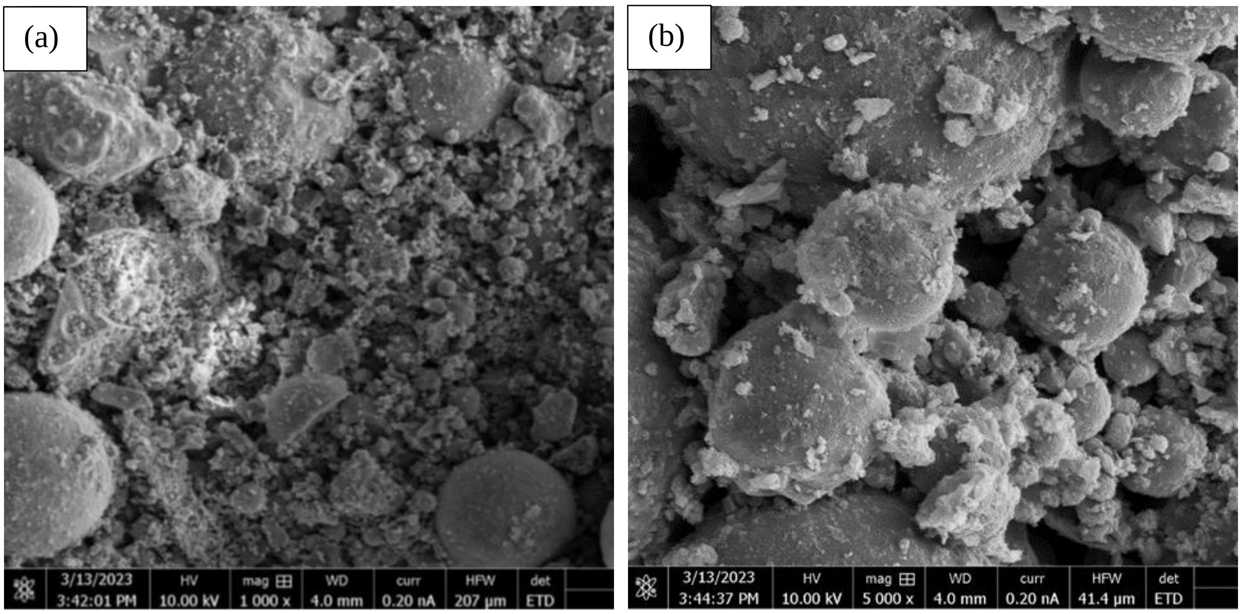


Figure 11: FESEM Image of SFA - Existing 2: (a) 1000x magnification and (b) 5000x magnification

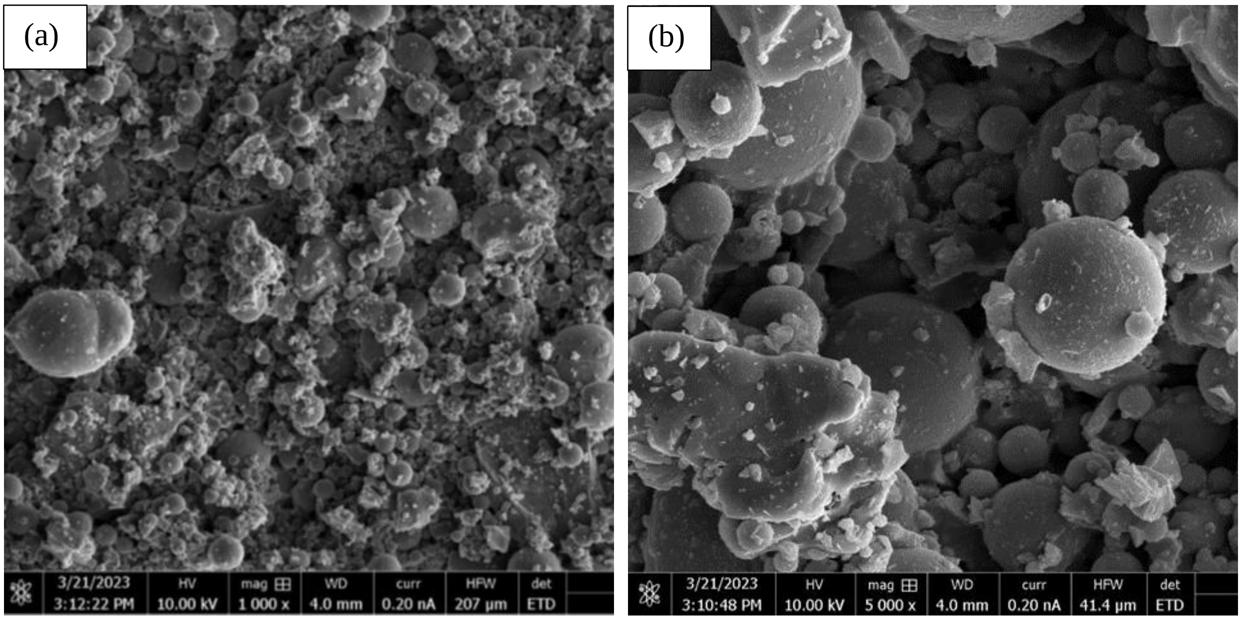


Figure 12: FESEM Image of CFA - Silo: (a) 1000x magnification and (b) 5000x magnification

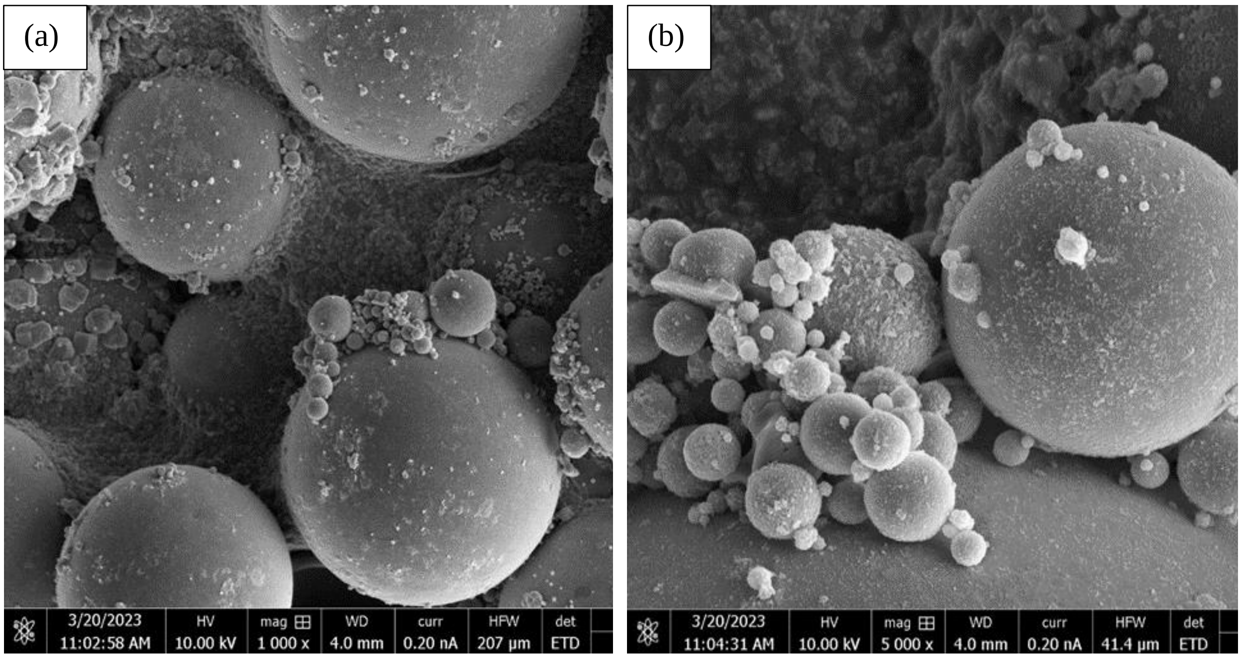


Figure 13: FESEM Image of Cenosphere: (a) 1000x magnification and (b) 5000x magnification

3.2 Chemical Components

Chemical components of the ashes obtained using FESEM can also be used in conjunction with EDS to determine the elemental composition of ash particles. According to the results, the ash particles were found to contain significant quantities of C, O, F, Na, Mg, Al, Si, S, K, Ca, Ti, Fe and Au. Table 2 presents the element content of all ashes.

Table 2: Element of Ashes

Element	Atomic (%)								
	CBA (Existing)	**CBA (New-Dry)**	**CBA (New - Wet)**	**SFA (Existing 1)**	**SFA (Existing 2)**	**SFA (New - Dry)**	**SFA (New - Wet)**	**CFA (New)**	**Cenosphere**
C	46.00	29.85	21.33	26.32	26.36	32.97	32.61	22.50	11.38
O	20.17	43.18	46.72	45.65	43.45	35.11	39.04	47.14	52.57
F	23.71	4.14	4.68	6.55	7.30	9.78	5.84	4.19	4.87
Na	0.05	-	0.14	0.12	0.25	0.27	0.33	0.19	0.37
Mg	0.11	0.27	0.34	1.58	1.23	1.27	0.75	0.11	0.54
Al	2.77	6.64	8.97	4.33	5.14	4.30	7.10	5.28	8.22
Si	4.42	10.48	13.17	11.42	10.97	9.84	10.32	17.93	17.67
Si	0.46	0.66	0.85	0.49	0.50	1.05	0.71	0.57	0.69
K	0.18	0.56	0.31	0.36	0.28	0.38	0.35	0.31	1.18
Ca	0.28	3.45	1.91	1.65	2.93	2.89	1.56	0.61	0.47
Ti	0.08	0.51	0.17	0.25	0.32	0.13	0.33	0.34	0.46
Fe	1.42	0.04	0.86	1.01	1.20	1.54	0.63	0.56	1.13
Au	0.35	0.31	0.54	0.28	0.07	0.45	0.44	0.27	0.46

3.3 Chemical Composition (Oxide)

Chemical composition of ashes was measured using X-ray fluorescence (XRF). The type of XRF used in testing is handheld XRF Analyzer (S1 Titan, 800) which are suitable for on-site soil testing, mineral, alloys, food safety and Archeology. The application selected for the sample analysis is Geoexploration with calibration of oxide phase. Table 3 presents the elements detected in sample ashes in unit percentage (%). Various materials are evident in the ash sample. According to the XRF results for cenosphere samples from different sources, silicon dioxide and aluminum oxide constitute the majority of the composition, significantly outweighing other element oxides, which are present only in small quantities.

The chemical composition of ashes was evaluated to classify the materials either as cementitious or pozzolanic, in accordance with ASTM C618. Based on ASTM C618, the formula for determining the properties of the classes is.

Class F (pozzolanic): Sum of $SiO_2 + Al_2O_3 + FeO_3$, min % ≥ 70.00 (Equation 4.1)

Class C (cementitious): Sum of $SiO_2 + Al_2O_3 + FeO_3$, min % ≥ 50.00 (Equation 4.2)

According to ASTM C618, Class F materials are normally produced from burning anthracite or bituminous coal, and they contribute to pozzolanic properties, while Class C materials are normally produced from lignite or sub-bituminous coal, and they also have pozzolanic properties as well as some cementitious properties. $SiO_2 + Al_2O_3 + FeO_3$, for all ashes are more than 70%. That belonged to Class F with pozzolanic properties and with an SO3 content that was lower than 4 %[25].

Table 3: Oxide compositions found in ash samples.

Oxide	CBA (Existing)	CBA (New-Dry)	CBA (New - Wet)	SFA (Existing 1)	SFA (Existing 2)	SFA (New - Dry)	SFA (New - Wet)	CFA (New)	Cenosphere
SiO_2	61.953	55.077	54.139	57.1400	53.709	54.687	56.937	67.153	59.42

Al_2O_3	22.335	24.643	23.052	22.1080	19.426	20.756	22.768	20.263	21.084
CaO	3.842	4.955	4.450	2.8680	5.113	4.734	2.455	1.332	0.907
Fe_2O_3	5.856	4.729	5.283	3.920	10.019	6.758	3.247	3.418	3.205
K_2O	0.983	0.728	0.805	1.1260	0.936	1.022	0.806	0.778	1.893
SO_3	-	-	0.052	0.232	0.642	0.737	0.272	0.252	-
Total SiO_2 + Al_2O_3 + Fe_2O_3	90.834	83.168	83.154	82.201	90.144	84.449	82.473	83.709	82.9518
Class Categorized	F	F	F	F	F	F	F	F	F

3.4 Amorphousness

X-Ray diffraction analysis (XRD) is a non-destructive technique that provides information about the crystallographic structure, chemical composition, and physical properties of a material. The type of instrument used is Bruker S2 Ranger. X-ray diffraction (XRD) serves as a method for analyzing the crystalline properties of a material. Graph patterns derived from XRD analysis can discern whether the material is in an amorphous, partially crystalline, or crystalline state. In Figure 22-30, the line graphs of XRD analysis for ash samples illustrate peaks appearing on a 2θ scale of 20 º to 30 º, signifying the presence of SiO2 within the ash samples. The gradual dense scattering observed in the XRD graph suggests the amorphous nature of the material. However, distinguishing between fully amorphous and fully crystalline samples in the XRD graph is indicated by a smooth gradual scatter for fully amorphous material and a flat, sharp peak for fully crystalline material.

Two phases could be observed in the diffractogram: an amorphous phase (reactive material), and a larger percentage of a crystalline phase, comprised of quartz and mullite (silicates) [26]. To achieve a highly reactive ash as a cement replacement material, the crystalline structure of the silica present in the ash is very important. High pozzolanic reactivity can be achieved if the amorphous silica present is of high quality[27]. CBA, SFA, CFA and cenosphere has significantly more amorphous phases of silica and alumina, and this has a positive effect on the strength[28].

Figure 14 Mineral Morphology for CBA (New-Dry)

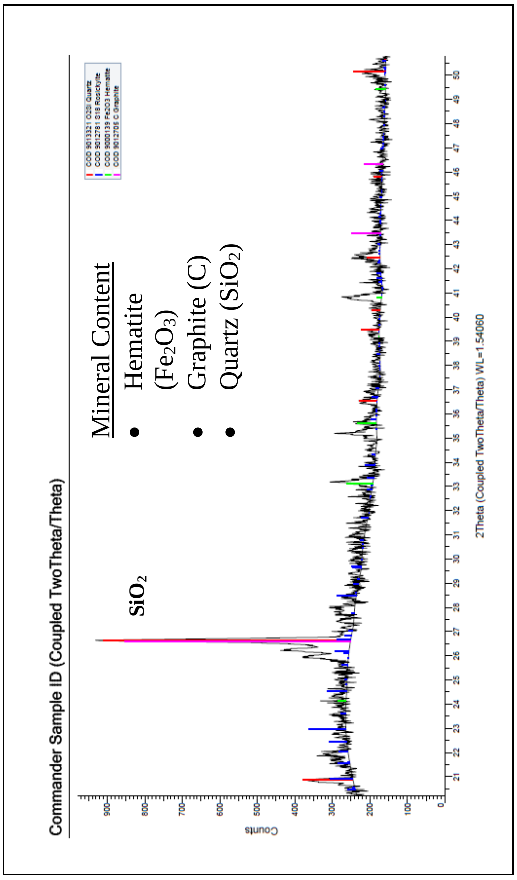


Figure 15 Mineral Morphology for CBA (Existing

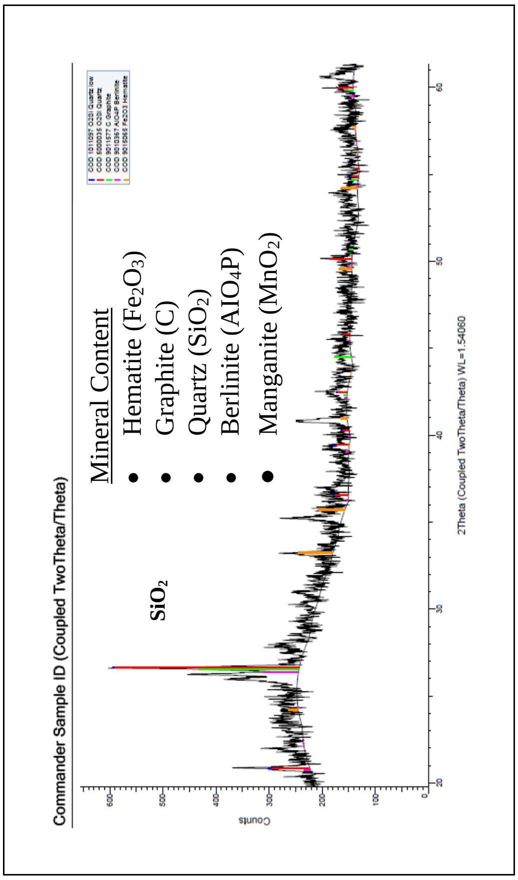


Figure 16 Mineral Morphology for CBA (New-Wet)

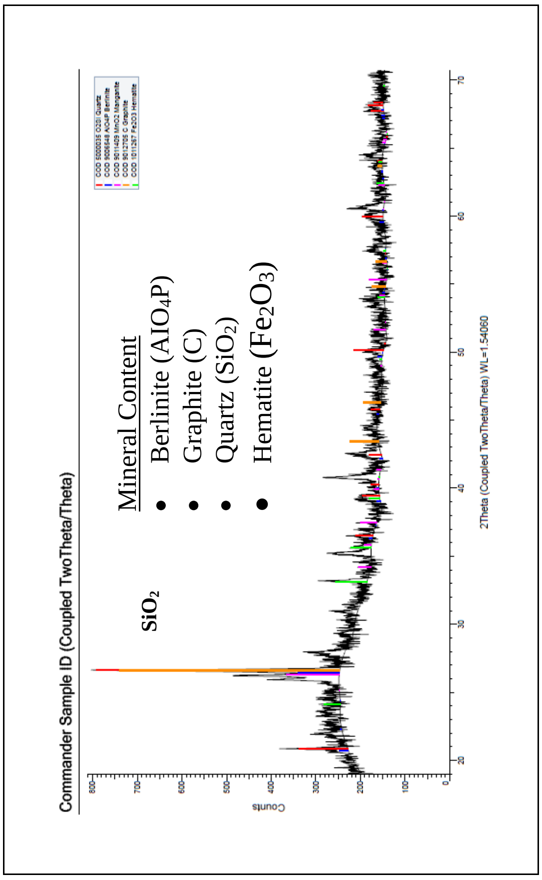


Figure 17 Mineral Morphology for SFA (Existing 1)

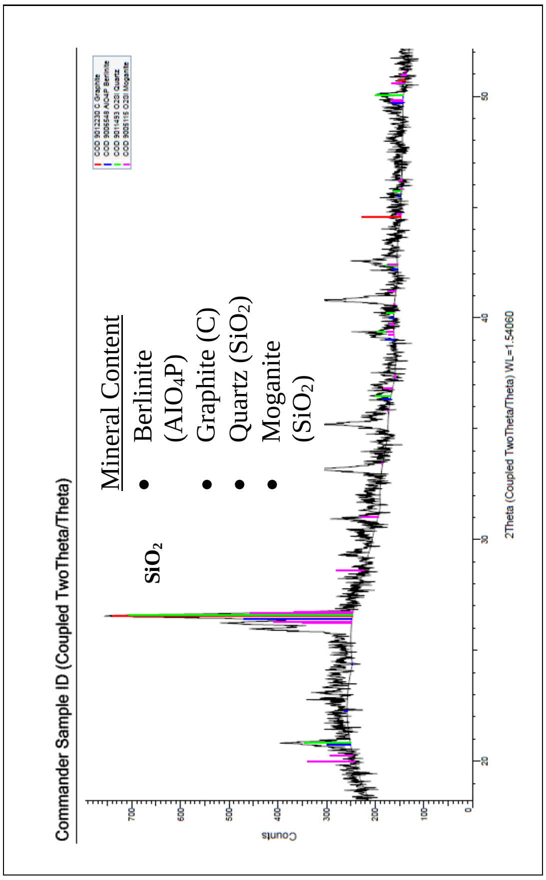


Figure 18 Mineral Morphology for SFA (New-Wet)

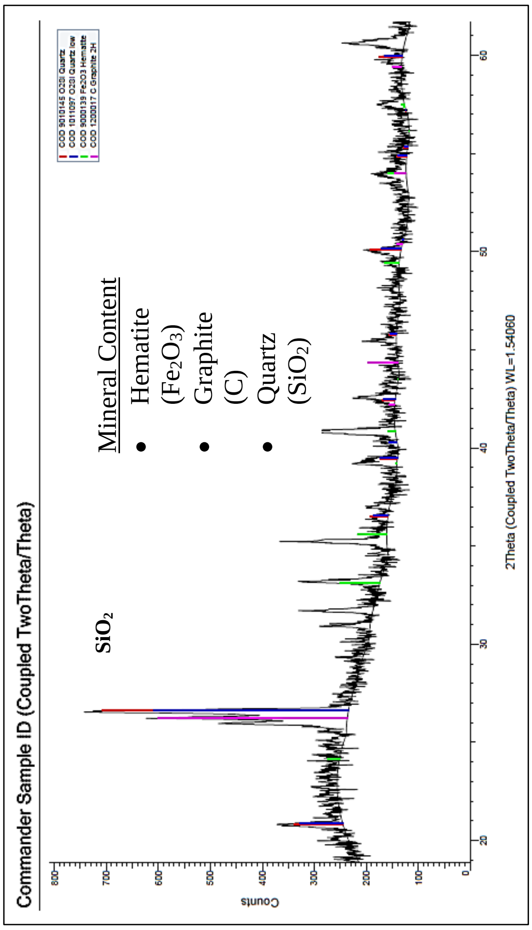


Figure 19 Mineral Morphology for SFA (New-Dry)

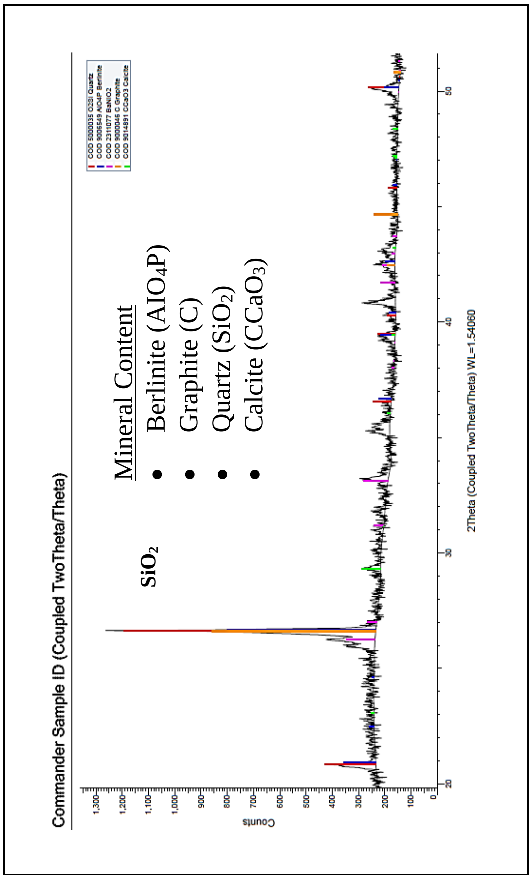


Figure 20 Mineral Morphology for CFA (New)

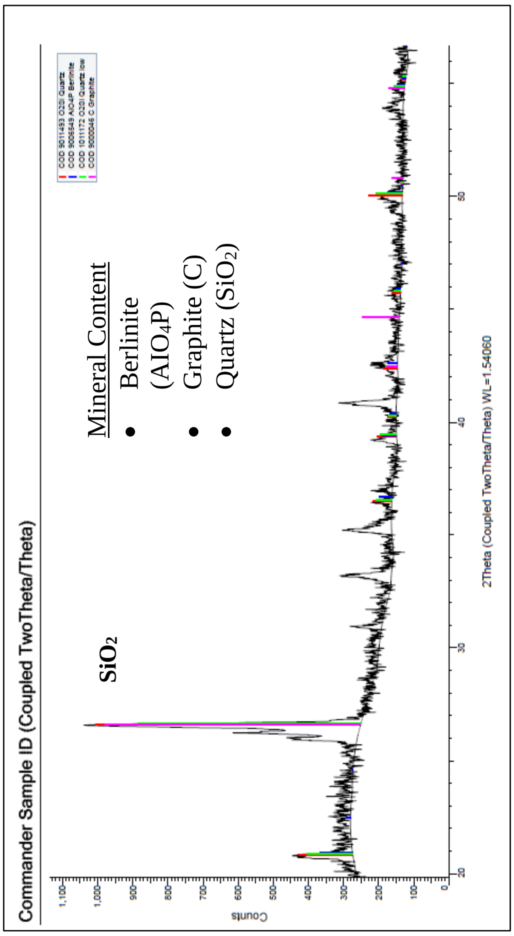


Figure 21 Mineral Morphology for SFA (Existing 2)

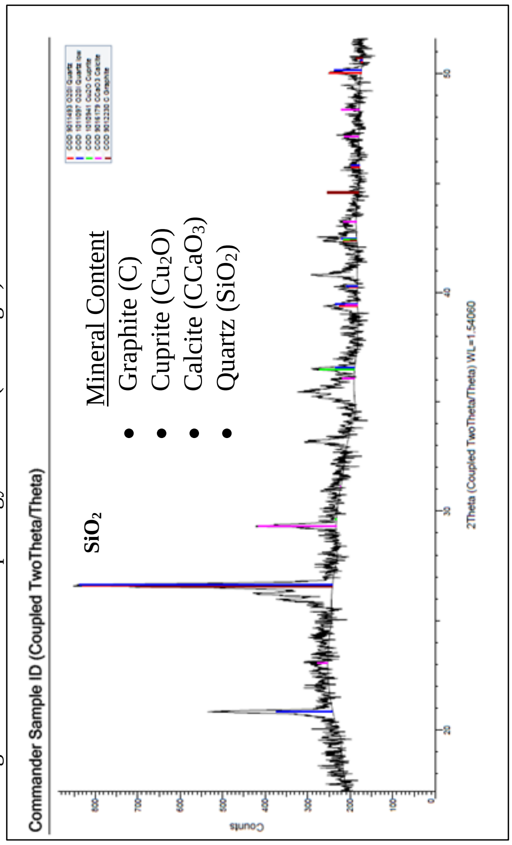
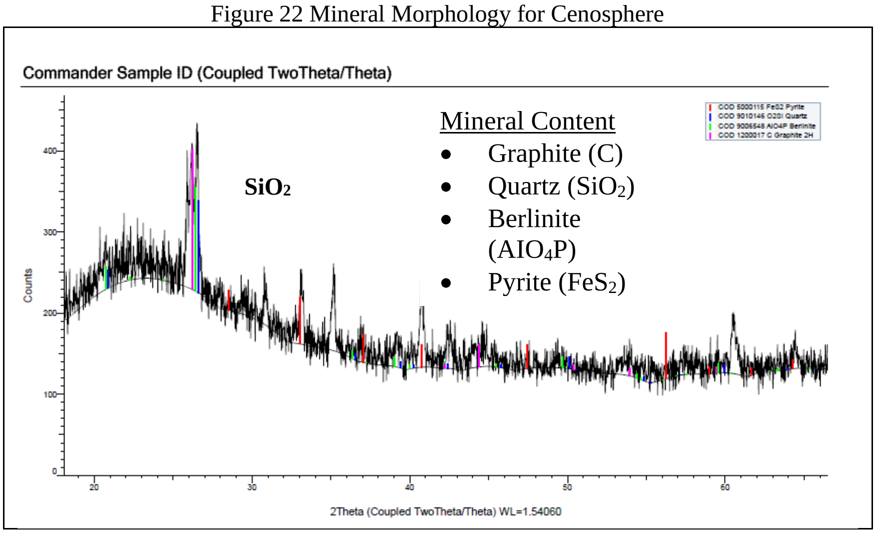


Figure 22 Mineral Morphology for Cenosphere



3.5 Particle Size Distribution (PSD)

Particle Size Distribution (PSD) serves as a metric used to represent the range of particle sizes present in a sample, expressed as percentages relative to the total number of particles, which sums up to 100%. The cumulative PSDs results of all the analysed samples give the shapes of the measured grain size distributions over different particle size ranges, which are similar to mono peaks. The summary of particle size distribution of the ashes is tabulated in Table 8. From the table, it is shown that the particle size of the existing sample obtained larger than the new sample. It could be due to the agglomeration on the ash pond[29].

The particle size of ashes fluctuates depending on the effective concrete mix, particularly when aggregates are well graded, facilitating optimal particle packing. Improved particle packing reduces the amount of cement needed to cover the particles, with any excess cement serving as lubrication to enhance workability. Incorporating ashes as a replacement for fine aggregates in traditional concrete leads to a reduction in compressive strength. However, this drawback can be mitigated by the addition of nano-silica [30].

Table 8: Summary of particle size distribution of the ashes

Sample	Particle Size Distribution	
	Min (μm)	**Max (μm)**
Cba (Existing)	20.0	50.0
Cba (New-Dry)	2.0	5.0
Cba (New - Wet)	2.0	5.0
SFA (New - Dry)	2.0	5.0
SFA (New - Wet)	2.0	5.0

SFA (Existing 1)	5.0	20.0
SFA (Existing 2)	20.0	50.0
Cfa (New)	5.0	20.0
Cenosphere	5.0	20.0

4.0 Conclusion

Material characterization such as Surface Morphology, Chemical Components, Chemical Composition (Oxide), Amorphousness and Particle Size Distribution of CBA, CFA, SFA and Cenosphere has been analyzed and showing the potential of using it as buildings' construction materials.

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