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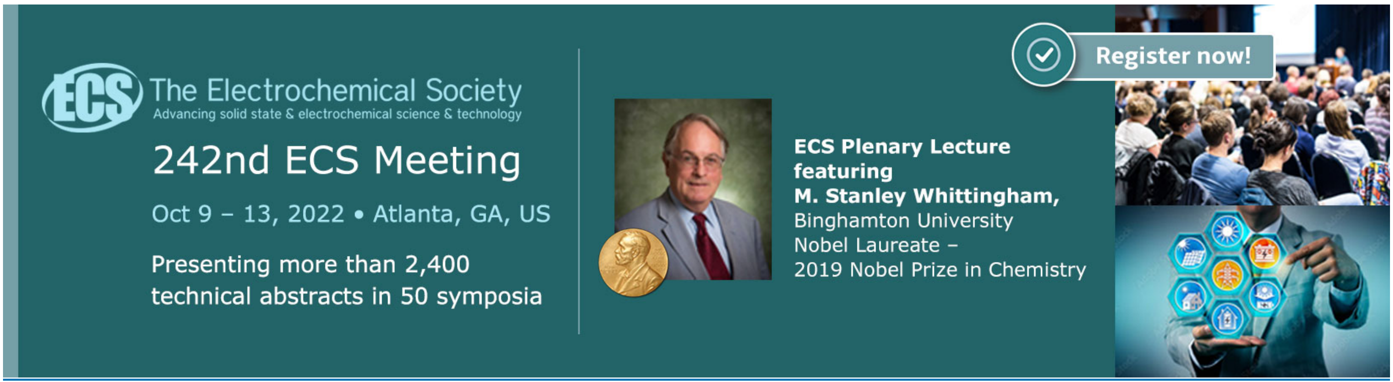

Recycling of coal bottom ash (CBA) as cement and aggregate replacement material: a review

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Abstract. The construction sector is a significant contributor to greenhouse gas emissions that contribute to global warming. Therefore, utilizing ‘green and recycled by-products’ in construction is a measure towards a sustainable future. Coal Bottom Ash (CBA) generated from thermal power plants has increases in production. This causes disposal problems. However, due to the ongoing depletion of natural limestone in cement production and aggregate in construction, this material may be used as a recycled construction material. This paper presents a comprehensive analysis of CBA’s physical and chemical properties and the impact on the use of CBA as aggregate or cement. A small volume of CBA can substitute fine aggregates without compromising the strength of the concrete. Further research remains to be carried to explore the potential of this material in producing concrete with enhanced strength.

1. Introduction

Coal is the main fuel for energy production in almost every country in the world. The largest coal plants are found in North America, Russia, Europe, China, and Australia [1, 2]. In 2014, approximately 18 million tonnes of coal bottom ash (CBA), which is the incombustible leftover part of the incinerated waste, came from coal plants in Europe [3]. It is estimated that there are more than 850 gigatonnes of proven coal reserves around the world, which would last for more than 130 years, with the current rates of production [4]. The solid wastes collected from these industries are referred to as coal combustion products (CCP) and can be categorized as coal fly ash (CFA), coal bottom ash (CBA), boiler slag (BS), and flue gas desulfurization (FGD) solids [5]. Approximately 40% of these wastes are used in a variety of applications, while the remaining 60% are managed in storage and disposal sites [6]. In general, coal is composed primarily of carbon and hydrogen, with some mineral matters, such as clay, quartz, shales, and calcite [7]. The percentages of these matters vary based on coal types and sources [7]. The quantity of CBA produced at a thermal power plant depends on the amount of coal burned, combustion conditions, and the amount of mineral and other metal compounds in the coal. According to the Environmental Protection Agency (EPA), living next to a coal ash disposal site could increase human health risks of cancer and other diseases. However, significant quantities of minerals and metals present in the residues offer various opportunities for reutilizing. Production and utilization of CCP by-products are shown in Table 1 [8].

Table 1. Production and usage of coal waste by-products (kilo tonnes) **[8]**

Country	**Australia**	**Canada**	**EU**	**Japan**	**USA**
Year	2012	2009–2011	2009	2003	2012
Production	12,797	7,042	51,806	9,870	109,750
Utilization	5,385 (42.1%)	1,724 (24.5%)	47,755 (92.2%)	8,380 (84.9%)	51,887 (47.3%)
Type of utilization					
Cement based materials	1,904	581	5,958	6,327	5,324
Construction application	361	1,010	20,417	1,014	27,901
Mining application	81	97	Incorporated in construction work	204	12,812
Geotechnical purpose	41	-	20,633	93	510
Agriculture	0.6	-	59	79	683
Waste stabilization	34.5	-	206	5	3,053
Others	2,963	36	482	658	1,604
References[a]	ADAA, 2012	CIRCA, 2013	ECOBA, 2009	JCOAL, 2003	ACAA, 2012

[a] Ash Development Association of Australia (ADAA); Association of Canadian Industries Recycling Coal Ash (CIRCA); European Coal Combustion Products Association (ECOBA); Japan Coal Energy Center (JCOAL); American Coal Combustion Products Association (ACAA).

Numerous recycling industries prefer to deal with CFA compared to CBA due to its beneficial characteristics. CFA particles are very fine and easy to bind and solidify. Especially when combined with water, making them an ideal constituent in concrete and the production of wallboards. These coal products were found to be stronger than those from virgin or raw materials and the recycling methods would render the toxic elements within CFA harmless. The use of CFA has more than doubled since the mid-1990s. More than 40% of the United States' CFA production is re-processed into cement, road base, drywall, bauxite, shingles, and plastic filler. On the other hand, CBA is barely as useful as CFA, even though the coal-fired power plant industry has tried to develop beneficial options, such as geotechnical fill and road-base filling material. This is because CBA would remain toxic even after it has been recycled. Since scrap metal recovery rate depends on the different compositions and technology used, some metals, such as aluminum, would be able to dissolve in water and produce gas that may cause an expansion in concrete, which is a significant concern over the failure of products containing this type of ash [9, 10]. Hence, these metal compounds must be reduced before the ash can be utilized.

2.0 Properties of CBA

2.1 Physical and Chemical Properties of CBA

CBA is comprised of inert, non-combustible materials that are leftover or retained after the combustion process. It comes in various forms of sand, stones, and ashes. Physically, these particles are porous, dark grey in color, angular and irregular in shape, rough texture, well-graded, and lighter than the natural aggregate [11]. It may also contain metals that would remain in the residual waste. Figure 1 shows the appearance of CBA after the incineration process, and Figure 2 shows the scanning electron microscope (SEM) images, which show CBA particles having disordered shapes. The size of this industrial waste varies from fine sand to gravel.

Figure 1. Coal bottom ash [12]

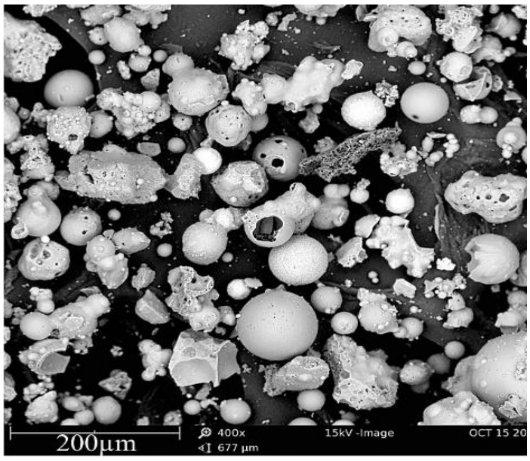


Figure 2. SEM images of coal bottom ash [13]

Table **2** lists the physical properties of CBA according to previous literature studies. The range of specific gravity varies from 1.39 to 2.47. Its unit weight and density were reported to be 948 and 2,190 kg/m^3, respectively. CBA has been identified to have a specific gravity that ranges between 1.39 and 2.47, which categorizes it as less dense than the typical value of natural sand (2.65). However, the density of CBA still depends on how the material was processed. CBA samples that underwent a screening process had an average specific gravity of 2.37, with most in the range from 2.2 and 2.5 [14]. Meanwhile, samples that were sieved into fine aggregates had an average specific gravity of 2.34, which was less dense than the coarse fractions [15-18]. Findings on CBA samples that underwent metal recovery (ferrous and non-ferrous metal exclusion) and pre-treatment (washing) showed that its specific gravity was 2.2 due to the elimination of metal elements, such as aluminium (Al), copper (Cu), iron (Fe), and lead (Pb). Different specific gravity values reported for CBA could be influenced by the additional mechanical treatment, namely, grinding the particles into a smaller size. This grinding process may reduce porosity while simultaneously increase the density.

Table 2. Physical properties of CBA according to previous studies

Properties	**Value**	**Sources**
Specific gravity	1.39 – 2.47	[19-24]
Loose bulk density (kg/m^3)	620	[19, 25]
Compacted bulk density (kg/m^3)	660	[19, 25]
Unit weight (kg/m^3)	948	[19]
Density (kg/m^3)	2190	[19]
Fineness modulus	1.37 – 3.44	[19, 22, 24]
Water absorption (%)	5.45 – 32.2	[19, 22, 24, 26, 27]
Clay lumps and friable particles (%)	2.0–2.4	[19]
Loss of ignition (LOI)	3.8	[21]

One of the unique characteristics of CBA is the tendency of the particles to absorb water. High water absorption ranging from 5.45% to 32.2% had been reported by previous researchers (

Table **2**). This value means that the absorption properties of CBA particles are greater than the natural fine aggregate, which is in the range of 1% to 3% [28]. Other studies have reported different sizes of CBA, which indicated that a small fraction would typically have a higher absorption index value that could be influenced by larger specific areas [29-32]. Meanwhile, CBA from the Tanjung Bin Power Plant, Malaysia [33] has CBA particle size distribution that was similar to natural river sand. The test was conducted by sieving river sand and CBA using different sieve sizes measuring 10 mm, 5 mm, 2.36 mm, 1.18 mm, 600 µm, 300 µm, and 150 µm. The results showed that CBA would be an ideal material in enhancing the strength properties of concrete. In other types of processing CBA in industries, large fractions of 30, 40, or 50 mm are customarily removed as part of a standard screening process. Figure 3 shows the particle distribution curve of CFA and CBA with an additional grinding step before being utilized in concrete, as studied by Argiz et al. [21].

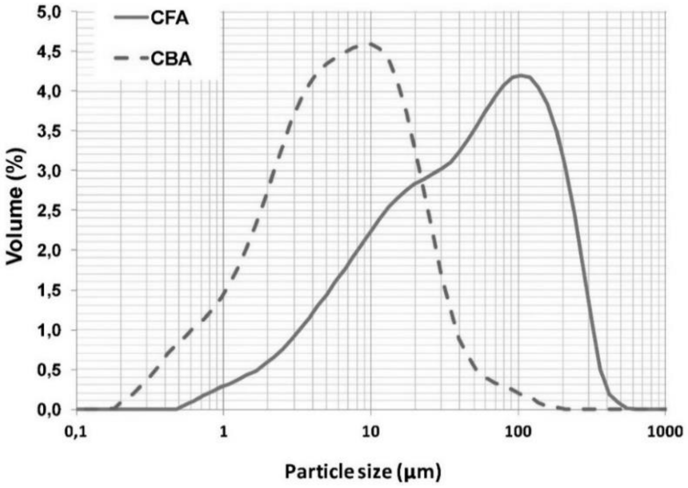


Figure 3. Granulometric distribution of CFA and ground CBA[21]

CBA in this study was ground using laboratory mill (48-L) capacity to reach a residue of 3% on a 450 µm. Further changes to the grading size of CBA were reliant on the plant operation and end-use of the material, which included sieving and grinding, as well as treatment via ferrous and non-ferrous removal. Chemically, the composition of CBA varies based on the nature of the materials used to incinerate, the process of burning, and further treatment [34]. Commonly, CBA is composed of 1% of unburnt or non-combustible materials, 9% of glass cullet, 10% of metals (ferrous at 8% and non-ferrous at 2%), 40% of ash, and 40% of melting products [35]. Table 3 lists the chemical composition of CBA reported by previous studies.

Table 3. Chemical oxide composition from previous studies

Component/ Sources	**[21]**	**[36]**	**[37]**	**[38]**	**[22]**	**[39]**
SiO_2	52.4	59.82	52.5	48.0	45.3	56.44
Al_2O_3	27.5	27.76	17.65	20.1	18.1	26.24
Fe_2O_3	6.6	3.77	8.3	8.77	19.84	8.44
CaO	2.4	1.86	4.72	7.11	8.7	0.75
MgO	1.83	0.7	0.58	3.13	0.969	0.4
SO_3	-	1.39	0.84	-	0.352	0.24
K_2O	3.48	1.61	-	-	2.48	1.29

Na_2O	0.36	0.33	-	-	-	0.09
TiO_2	0.97	-	2.17	1.11	3.27	3.36
CI	0.006	-	-	-	-	-
P_2O_5	0.12	-	-	-	0.351	-
Loss on ignition	3.8	4.69	4.01	8.10	-	0.89

The main oxides present in CBA are SiO_2 (45.3% – 59.82%), and Al_2O_3 (17.65% – 27.76%), while Fe_2O_3 (3.77% – 19.84%), K_2O (1.29% – 3.48%), CaO (0.75% – 8.7%), and MgO (0.40% – 3.13%) were also identified in smaller quantities. The CBA was found to have a range of loss of ignition (LOI) between 0.89 – 8.10. A high LOI value, as influenced by its organic compounds and other impurities, such as carbon, may compromise the structural integrity and mechanical performance of the material. The observed difference in those mentioned above chemical and physical properties was probably due to the changes in different combustibles conditions, such as ash temperature, duration, and the fuel used. Additional pre-treatment step for CBA samples is needed to reduce the LOI value before it can be effectively used in concrete. In terms of elemental composition, Si, Fe, Ca, and Al are the most abundant elements in CBA [14]. Several toxic elements, such as Zn, Cu, Pb, Cr, Ni, Cd, and As were found in smaller percentages. However, these toxic metal compounds are essential elements to consider during the Environmental Impact Assessment (EIA) of leaching risks. The existence of aluminum in CBA has become an issue due to the formation of hydrogen gas in the cementitious system [10, 40-42]. Quartz is the most abundant element found in CBA, along with other minerals (calcite, hematite, magnetite, and gehlenite). Other peaks detected by XRD in CBA were silicates, aluminates, aluminosilicates, sulfates, oxides, and phosphates [43, 44]. The high amount of silicon and calcium in CBA shows its significant potential to be utilized as a cementitious based material. As well, the amorphous phase was detected in CBA [45] along with high-intensity crystalline peaks of quartz (SiO_2), calcite ($CaCO_3$), and calcium aluminate silicate ($CaO.Al_2O_3.4SiO_2$), with a low glassy phase in the XRD results (shown in Figure 4). The glass contents ranging mostly from 15% to 70% [34, 46-48].

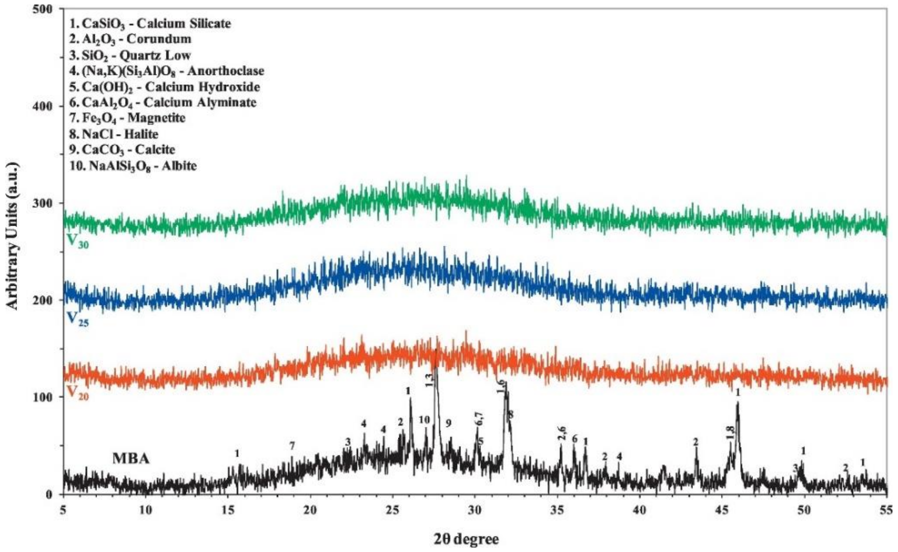


Figure 4. X-ray diffraction patterns of coal bottom ash[45]

2.2 Pozzolanic properties of CBA

In terms of pozzolanic reactivity, CBA is less favorable compared to CFA because its physical and chemical properties lack the criteria of a good pozzolan. In general, several factors must be considered before CBA can be labeled as a pozzolanic material. The main criteria of a good pozzolan include the total amount of silica, alumina, and iron content, particle fineness, and the degree of amorphousness. A pozzolanic reaction will only begin when there is a consumption of silica content from the ashes by the hydration product of calcium hydrate to form additional calcium silicate hydrate (C-S-H) in the cementitious system. Thus, the additional formation of C-S-H will improve the strength and durability properties of concrete. Therefore, higher amorphous silica content in a pozzolan will increase its pozzolanic performance. In Malaysia, CBA is infrequently used as a pozzolanic material in cementitious-based products. This is mainly due to insufficient knowledge regarding the proper use of CBA. In terms of silica content, Wongsa et al. [49] reported that the composition of CFA was similar to CBA, in which both contained 74.4% and 72.2% of silica oxide, 16.6% and 16.5% of aluminium oxide, and 2.4% and 2.6% of iron oxide, respectively. Therefore, the total amount of these three chemical oxides were higher than 70%, which was in agreement with ASTM C 618 for pozzolanic materials, class F [50]. However, most of the previous studies suggested that the fineness of CBA should be increased since the raw ash would come in the particle size range of 0.1 to 5 mm, or more than 95% retained on a sieve No. 325 [51-53].

Pozzolanic performance of CBA studied by Cheriaf et al. [52] revealed that the pozzolanic reaction proceeded slowly at the early age of curing and started to accelerate after 28 days, which was similar to CFA. However, Kim and Lee [23] reported that strength and pozzolanic performance varied when different particle sizes were used. They concluded that bottom ash that passes through sieve No. 40 (425 µm) would be able to achieve similar strength as fly ash mortar. Meanwhile, Oruji et al. [53] revealed that when the median particle size of 4.5 µm was used as a cement replacement, it showed a higher strength value compared to conventional mortar, with replacement of up to 33.3% by weight of mortar binder at 28 days. Oruji et al. [53] summarised that the particle size and age of curing, in terms of strength and level of replacement, had affected the strength activity index performance (SAI) of mortar to lower than the SAI of fly ash mortar by approximately 7%.

2.3 Strength properties of concrete containing CBA

Several studies focused on concrete production that incorporates bottom ash and fly ash either as cement, sand or aggregate replacement. These investigations have verified that the incorporation of CBA to replace fine aggregates had shown comparable strength results with the control specimen [19, 54-56]. It was reported that at 28 days of curing, a significant difference was observed in compressive strength between CFA and CBA specimens at 25% of partial cement replacement [56]. The researchers reported that the strength activity index at 28 days for both coal ash types had complied with the limit of not exceeding 0.75, according to EN 196 [57] and ASTM C311 [58]. Based on the overall data, Sigvardsen and Ottosen [56] concluded that the CBA had shown a more substantial positive contribution to compressive strength through its pozzolanic reactions compared to CFA based on SAI values. Figure 5 shows the strength development of coal ash at 14, 28, and 90 days of curing.

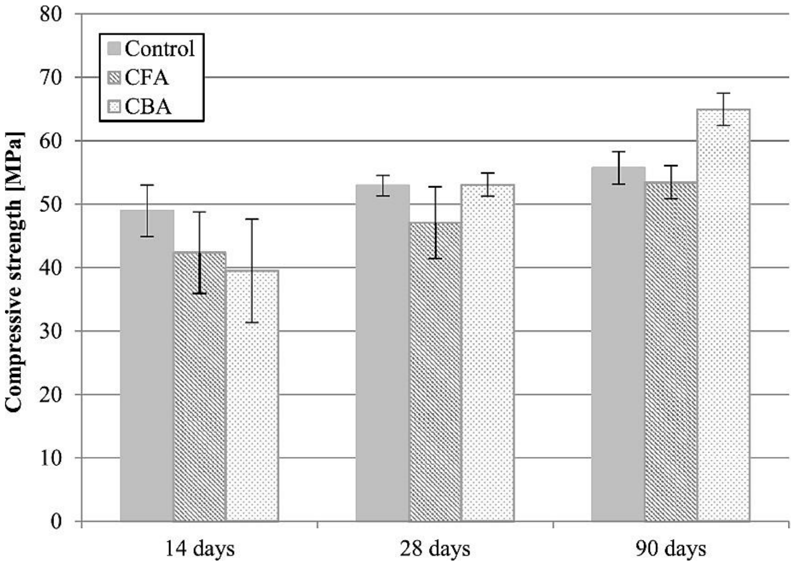


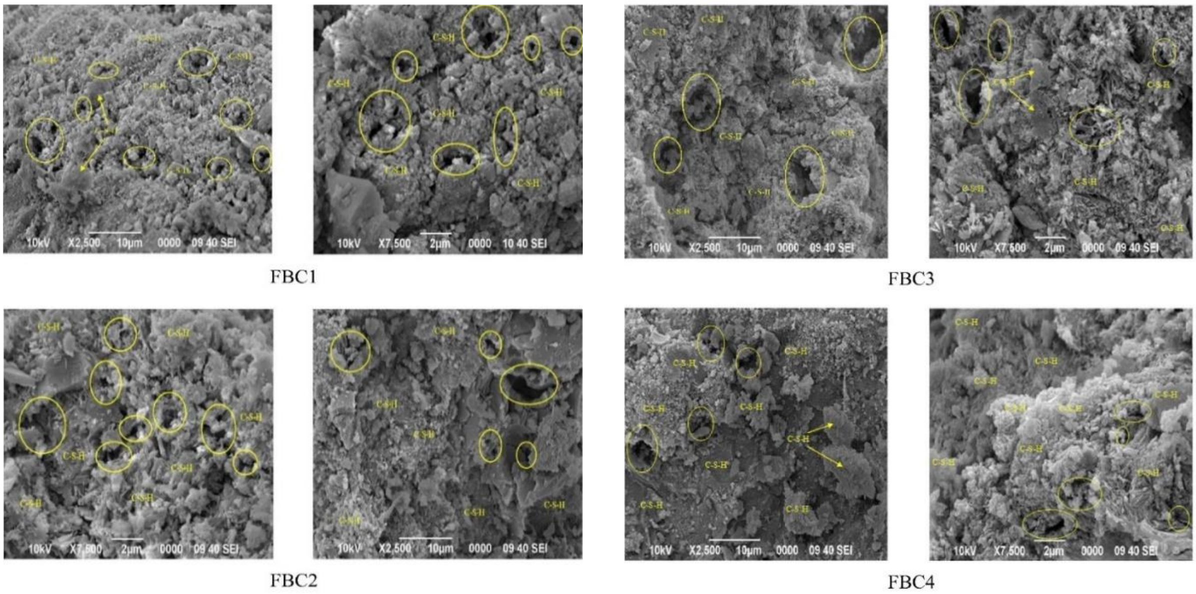
Figure 5. Compressive Strength of CBA and CFA at 25% replacement of cement [56]

The combination of CFA and CBA has been investigated as sand and cement replacement in concrete [22]. The results showed similar trends in terms of the workability of concrete. In the early age of curing, which was less than 28 days, no significant difference was observed in the compressive, flexural, and tensile strengths of all concrete samples when compared to control. The compressive strengths of different combinations of CFA and CBA are as shown in Table 4.

Table 4. Mixture proportion of concrete containing CBA and CFA [22]

Mixture proportion	CBA %	CFA %
FBC1	25	20
FBC2	50	20
FBC3	75	20
FBC4	100	20

After 91 days of curing, FBC1 has increased strength performance to 96.98%, FBC2 has increased to 100.2%, FBC3 has increased to 99.18%, and FBC4 has increased to 98.17% compared to the control specimen. This trend was attributed to the pozzolanic activity by CBA and CFA in the specimens. This performance may also be influenced by the number and size of voids, which were not as monolithic and compact as in the control specimen, shown in Figure 6. Based on Figure 6, the formation of an imprecise C-S-H gel and a higher percentage of voids had affected their compressive strength at the early age of curing. Other advanced applications of CBA are as coarse aggregate replacement in high strength concrete that has shown numerous advantages. The strength performance of concrete with 100% bottom ash aggregate was comparable to the conventional concrete (equal amounts of water and binder materials were used) [59]. Furthermore, some studies revealed that the common issues of chloride attack and shrinkage in high strength concrete were reduced using the replacement with bottom ash aggregates [21, 37]. The results of these studies have indicated that the application of ground bottom ash as supplementary cementitious material (SCM) in concrete could reduce the adverse effects of chloride penetration.


FBC1

FBC3

FBC2

FBC4

Figure 6. SEM images of BA and FA at 28 days in concrete [22]

Other advanced applications of CBA as cementitious composites had also shown positive contributions in terms of strength performance. Kurama et al. [60] studied the use of bottom ash in aerated cementitious composites to produce Aerated Autoclaved Concrete (AAC). Notable improvement when using CBA as a replacement for quartz sand was reported. The formation of tobermorite in the composite cement matrix was enhanced, owing to the high pozzolanic activity; hence, strength increment was achieved with lower density. Güllü [61] conducted a series of experimental works on the utilization of CBA as grouting material. Before use, CBA was grounded to smaller than 10 µm and was combined with Portland cement in different ratios. The author found that grouting that incorporated CBA showed higher values than normal grouting, in terms of resistance to freeze and thaw performance.

3.0 Limitation of CBA as Construction Material

The utilization of CBA as aggregates and/or admixtures in different types of cement-based applications has been widely explored. However, it has been limited as a medium of cementitious product. The results from a series of laboratory works presented the strength performance, and its properties covering partial amounts of CBA were almost comparable to those of conventional concrete [39]. Some features from the unique physical and chemical characteristics of power plant waste might hinder a more extensive field application of bottom ash concrete. The first consideration is reduced in workability due to the interlocking characteristics of CBA. The physical texture of rough bottom ash particles has led to interlocking between aggregates in fresh mixtures, which decreased the flowability of concrete. Park et al. [62] have reported that even though the compressive strength of concrete incorporating CBA as coarse aggregate replacement had increased to 5% and the rate of substitution had increased to 25%, the slump was significantly reduced. The second consideration would be the risk of toxic elements leaching out from concrete containing CBA. Gong et al. [63] studied the in-situ leaching behavior of trace elements in a pond behind a power plant in the west of China. Some toxic trace elements in the soil were reported as higher than those found in normal soils, especially Cd. In some areas of the downstream river of the pond, the pH value and concentrations of Cr, Cd, Pb, Zn, and Cu were reported as higher than those from the upstream river due to the leachate from the ash pond. From the experimental results reported, the total toxic elements had exceeded the local water quality standards for ground and surface water resources. The third aspect deals with issues related to the unburned carbon in CBA. The amount of unburned carbon tends to hinder air entrainment in fresh concrete mixtures. It was reported that the content of unburned carbon in CBA could affect the compressive strength of concrete mixtures, which means that the compressive strength would increase with decreasing carbon content in the bottom ash [64]. Unburned carbon may also contain a certain amount of cenosphere floats on the surface of bleeding water, which might affect the aesthetics of concrete structures. Based on the above considerations, appropriate evaluation of the effect of pre-treatment for CBA should be addressed to demonstrate the use of CBA in mortar specimens with different levels of cement replacement as an alternative pozzolanic material. Further study in this area would also add new knowledge related to the utilization of CBA.

4.0 Conclusion

The limited reserve of natural limestone for cement production and aggregate construction is a challenge in the construction world. Application of CBA as a recycled construction can be the solution to this problem. However, an additional pre-treatment stage for CBA samples is required before it can be used effectively in concrete. This paper provides a detailed study of the physical and chemical properties of CBA and its application. The study further addresses the effect on the use of CBA as an aggregate and the replacement of cement. A minimal volume of CBA will replace fine aggregates without compromising the strength of the concrete. CBA has proven to be one of the most promising material in the application sustainable technologies in the construction industry. The CBA application will allow the planet to become greener by reducing greenhouse gas pollution from heavy industry.

5.0 References

[1] Barnes, "Ash Utilization- impact of recent changes in power generation practices," in "In I.E.A.C.C Centre (Ed.)," 2010, vol. 1.

[2] E. I. Diaz, E. N. Allouche, and S. Eklund, "Factors affecting the suitability of fly ash as source material for geopolymers," *Fuel*, vol. 89, no. 5, pp. 992-996, 2010/05/01/ 2010, doi: https://doi.org/10.1016/j.fuel.2009.09.012.

[3] N. S. Bentsen, C. Felby, and B. J. Thorsen, "Agricultural residue production and potentials for energy and materials services," *Progress in Energy and Combustion Science*, vol. 40, no. 0, pp. 59-73, 2014, doi: http://dx.doi.org/10.1016/j.pecs.2013.09.003.

[4] W. C. Association, vol. 12, 2012.

[5] A. C. A. Association, "Coal combustion product (CCP) production ans use survey results. ," 2008.

[6] Feuerborn, "Coal combustion products in europe, an update on production and utilisation, standardisation and regulation, in: Proceedings of World of Coal Ash (WOCA) " *Conference, May 9–12, 2011, Denver, USA.*, 2011.

[7] Q. Zhang, H. Ghanem, T. D. Branam, E. R. Elswick, and G. A. Olyphant, "Geochemical characterization of engineered coal-combustion byproducts (CCBs): Occurrence and mobility of trace elements, implications for interactions with acidic and ambient groundwater," *Fuel*, vol. 177, pp. 304-314, 8/1/ 2016, doi: http://dx.doi.org/10.1016/j.fuel.2016.02.083.

[8] J. H. Park, Edraki, Mansour, D. Mulligan, and H. S. Jang, "The application of coal combustion by-products in mine site rehabilitation," *Journal of Cleaner Production*, vol. 84, pp. 761-772, 12/1/ 2014, doi: http://dx.doi.org/10.1016/j.jclepro.2014.01.049.

[9] Y. Xia, P. He, L. Shao, and H. Zhang, "Metal distribution characteristic of MSWI bottom ash in view of metal recovery," *Journal of Environmental Sciences*, vol. 52, pp. 178-189, 2017/02/01/ 2017, doi: https://doi.org/10.1016/j.jes.2016.04.016.

[10] G. Pecqueur, C. Crignon, and B. Quénée, "Behaviour of cement-treated MSWI bottom ash," *Waste Management*, vol. 21, no. 3, pp. 229-233, 2001/06/01/ 2001, doi: https://doi.org/10.1016/S0956-053X(00)00094-5.

[11] M. Singh and R. Siddique, "Effect of coal bottom ash as partial replacement of sand on properties of concrete," *Resources, Conservation and Recycling*, vol. 72, pp. 20-32, 2013/03/01/ 2013, doi: https://doi.org/10.1016/j.resconrec.2012.12.006.

[12] r. Embong, "Pozzolanic and Strength Properties of Mortar Containing Chemically Pre-Treated Coal Bottom Ash," Doctor of Philosophy, Faculty of Engineering Technology, Universiti Malaysia Pahang, Malaysia, 2019.

[13] S. S. G. Hashemi, H. B. Mahmud, J. N. Y. Djobo, C. G. Tan, B. C. Ang, and N. Ranjbar, "Microstructural characterization and mechanical properties of bottom ash mortar," *Journal of Cleaner Production,* vol. 170, pp. 797-804, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.jclepro.2017.09.191.

[14] C. J. Lynn, R. K. Dhir Obe, and G. S. Ghataora, "Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete," *Construction and Building Materials,* vol. 127, pp. 504-517, 11/30/ 2016, doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.09.132.

[15] J. Forth, I. N. Thanaya, and S. Zoorob, *Development of bitumen-bound waste aggregate building block*. 2006, pp. 23-32.

[16] O. Ginés, J. M. Chimenos, A. Vizcarro, J. Formosa, and J. R. Rosell, "Combined use of MSWI bottom ash and fly ash as aggregate in concrete formulation: Environmental and mechanical considerations," *Journal of Hazardous Materials*, vol. 169, no. 1, pp. 643-650, 2009/09/30/ 2009, doi: https://doi.org/10.1016/j.jhazmat.2009.03.141.

[17] P. Tang, M. V. A. Florea, P. Spiesz, and H. J. H. Brouwers, "Characteristics and application potential of municipal solid waste incineration (MSWI) bottom ashes from two waste-to-energy plants," *Construction and Building Materials*, vol. 83, pp. 77-94, 2015/05/15/ 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.02.033.

[18] M.-H. Wu, C.-L. Lin, W.-C. Huang, and J.-W. Chen, "Characteristics of pervious concrete using incineration bottom ash in place of sandstone graded material," *Construction and Building Materials,* vol. 111, pp. 618-624, 2016/05/15/ 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.02.146.

[19] I. M. Nikbin, S. Rahimi R, H. Allahyari, and M. Damadi, "A comprehensive analytical study on the mechanical properties of concrete containing waste bottom ash as natural aggregate replacement," *Construction and Building Materials*, vol. 121, pp. 746-759, 9/15/ 2016, doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.06.078.

[20] S. S. G. Hashemi, H. B. Mahmud, T. C. Ghuan, A. B. Chin, C. Kuenzel, and N. Ranjbar, "Safe disposal of coal bottom ash by solidification and stabilization techniques," *Construction and Building Materials,* vol. 197, pp. 705-715, 2019/02/10/ 2019, doi: https://doi.org/10.1016/j.conbuildmat.2018.11.123.

[21] C. Argiz, A. Moragues, and E. Menéndez, "Use of ground coal bottom ash as cement constituent in concretes exposed to chloride environments," *Journal of Cleaner Production*, vol. 170, pp. 25-33, 2018/01/01/ 2018, doi: https://doi.org/10.1016/j.jclepro.2017.09.117.

[22] M. Rafieizonooz, J. Mirza, M. R. Salim, M. W. Hussin, and E. Khankhaje, "Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement," *Construction and Building Materials*, vol. 116, pp. 15-24, 2016/07/30/ 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.04.080.

[23] H. K. Kim and H. K. Lee, "Use of power plant bottom ash as fine and coarse aggregates in high-strength concrete," *Construction and Building Materials*, vol. 25, no. 2, pp. 1115-1122, 2011/02/01/ 2011, doi: https://doi.org/10.1016/j.conbuildmat.2010.06.065.

[24] M. Singh and R. Siddique, "Compressive strength, drying shrinkage and chemical resistance of concrete incorporating coal bottom ash as partial or total replacement of sand," *Construction and Building Materials*, vol. 68, pp. 39-48, 2014/10/15/ 2014, doi: https://doi.org/10.1016/j.conbuildmat.2014.06.034.

[25] Y. Isa and G. Ayten, "Properties of Concrete Containing Nonground Ash and Slag As Fine Aggregate," *Materials Journal*, vol. 104, no. 4, 7/1/2007 2007, doi: 10.14359/18829.

[26] A. Lazaro, G. Quercia Bianchi, H. J. H. Brouwers, and J. W. Geus, *Synthesis of a Green Nano-Silica Material Using Beneficiated Waste Dunites and Its Application in Concrete*. 2013.

[27] H.-K. Kim, "Utilization of sieved and ground coal bottom ash powders as a coarse binder in high-strength mortar to improve workability," *Construction and Building Materials*, vol. 91, pp. 57-64, 2015/08/30/ 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.05.017.

[28] A. M. Neville, *Properties of Concrete,fourth edition*. Longman, London, 1995.

[29] A. Keulen, A. van Zomeren, P. Harpe, W. Aarnink, H. A. E. Simons, and H. J. H. Brouwers, "High performance of treated and washed MSWI bottom ash granulates as natural aggregate replacement within earth-moist concrete," *Waste Management*, vol. 49, pp. 83-95, 2016/03/01/ 2016, doi: https://doi.org/10.1016/j.wasman.2016.01.010.

[30] D. Liu, L. Li, and H. Cui, "Utilization of municipal solid waste Incinerator Bottom Ash Aggregate in asphalt mixture," vol. 2, 2014, pp. 1169-1176.

[31] M. Izquierdo, Á. López-Soler, E. Vazquez Ramonich, M. Barra, and X. Querol, "Characterisation of bottom ash from municipal solid waste incineration in Catalonia," *Journal of Chemical Technology & Biotechnology*, vol. 77, no. 5, pp. 576-583, 2002/05/01 2002, doi: 10.1002/jctb.605.

[32] R. Siddique, "Use of municipal solid waste ash in concrete," *Resources, Conservation and Recycling*, vol. 55, no. 2, pp. 83-91, 2010/12/01/ 2010, doi: https://doi.org/10.1016/j.resconrec.2010.10.003.

[33] N. I. R. Ramzi, S. Shahidan, M. Z. Maarof, and N. Ali, "Physical and Chemical Properties of Coal Bottom Ash (CBA) from Tanjung Bin Power Plant," *IOP Conference Series: Materials Science and Engineering*, vol. 160, p. 012056, 2016/11 2016, doi: 10.1088/1757-899x/160/1/012056.

[34] A. P. Bayuseno and W. W. Schmahl, "Understanding the chemical and mineralogical properties of the inorganic portion of MSWI bottom ash," *Waste Management*, vol. 30, no. 8, pp. 1509-1520, 2010/08/01/ 2010, doi: https://doi.org/10.1016/j.wasman.2010.03.010.

[35] O. Holm and F.-G. Simon, "Innovative treatment trains of bottom ash (BA) from municipal solid waste incineration (MSWI) in Germany," *Waste Management*, vol. 59, pp. 229-236, 1// 2017, doi: http://dx.doi.org/10.1016/j.wasman.2016.09.004.

[36] X. Ge, M. Zhou, H. Wang, Z. Liu, H. Wu, and X. Chen, "Preparation and characterization of ceramic foams from chromium slag and coal bottom ash," *Ceramics International*, vol. 44, no. 10, pp. 11888-11891, 2018/07/01/ 2018, doi: https://doi.org/10.1016/j.ceramint.2018.03.122.

[37] S. A. Mangi, M. H. Wan Ibrahim, N. Jamaluddin, M. F. Arshad, and R. Putra Jaya, "Short-term effects of sulphate and chloride on the concrete containing coal bottom ash as supplementary cementitious material," *Engineering Science and Technology, an International Journal*, 2018/09/10/ 2018, doi: https://doi.org/10.1016/j.jestch.2018.09.001.

[38] S. Pyo and H.-K. Kim, "Fresh and hardened properties of ultra-high performance concrete incorporating coal bottom ash and slag powder," *Construction and Building Materials*, vol. 131, pp. 459-466, 2017/01/30/ 2017, doi: https://doi.org/10.1016/j.conbuildmat.2016.10.109.

[39] M. Singh and R. Siddique, "Properties of concrete containing high volumes of coal bottom ash as fine aggregate," *Journal of Cleaner Production*, vol. 91, pp. 269-278, 2015/03/15/ 2015, doi: https://doi.org/10.1016/j.jclepro.2014.12.026.

[40] Tyrer, "municipal solid waste incinerator (MSWI) concrete, in: Pacheco-Torgal et al. (Eds.)," *Eco-efficient concrete, Woodhead Publishing*, pp. 273-310, 2013.

[41] M.-C. Weng, M.-H. Wu, C.-L. Lin, D.-K. Syue, and C. Hung, "Long-term mechanical stability of cemented incineration bottom ash," *Construction and Building Materials*, vol. 93, pp. 551-557, 2015/09/15/ 2015, doi: https://doi.org/10.1016/j.conbuildmat.2015.06.039.

[42] U. Müller and K. Rübner, "The microstructure of concrete made with municipal waste incinerator bottom ash as an aggregate component," *Cement and Concrete Research*, vol. 36, no. 8, pp. 1434-1443, 2006/08/01/ 2006, doi: https://doi.org/10.1016/j.cemconres.2006.03.023.

[43] A. Wongsa, K. Boonserm, C. Waisurasingha, V. Sata, and P. Chindaprasirt, "Use of municipal solid waste incinerator (MSWI) bottom ash in high calcium fly ash geopolymer matrix," *Journal of Cleaner Production*, vol. 148, pp. 49-59, 2017/04/01/ 2017, doi: https://doi.org/10.1016/j.jclepro.2017.01.147.

[44] Z. Yang, S. Tian, L. Liu, X. Wang, and Z. Zhang, "Recycling ground MSWI bottom ash in cement composites: Long-term environmental impacts," *Waste Management*, vol. 78, pp. 841-848, 2018/08/01/ 2018, doi: https://doi.org/10.1016/j.wasman.2018.07.002.

[45] S. Papamarkou, D. Christopoulos, P. E. Tsakiridis, G. Bartzas, and K. Tsakalakis, "Vitrified medical wastes bottom ash in cement clinkerization. Microstructural, hydration and leaching characteristics," *Science of The Total Environment*, vol. 635, pp. 705-715, 2018/09/01/ 2018, doi: https://doi.org/10.1016/j.scitotenv.2018.04.178.

[46] K. Ruebner, F. Haamkens, and O. Linde, *Use of municipal solid waste incinerator bottom ash as aggregate in concrete*. 2008, pp. 459-464.

[47] K. Paine, R. Dhir, and V. P. A. Doran, *Incinerator Bottom Ash: Engineering and Environmental Properties as a Cement Bound Paving Material*. 2002.

[48] Y. Wei, T. Shimaoka, A. Saffarzadeh, and F. Takahashi, "Mineralogical characterization of municipal solid waste incineration bottom ash with an emphasis on heavy metal-bearing phases," *Journal of Hazardous Materials*, vol. 187, no. 1, pp. 534-543, 2011/03/15/ 2011, doi: https://doi.org/10.1016/j.jhazmat.2011.01.070.

[49] A. Wongsa, Y. Zaetang, V. Sata, and P. Chindaprasirt, "Properties of lightweight fly ash geopolymer concrete containing bottom ash as aggregates," *Construction and Building Materials*, vol. 111, pp. 637-643, 2016/05/15/ 2016, doi: http://dx.doi.org/10.1016/j.conbuildmat.2016.02.135.

[50] *Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete.*, A. C618, West Conshohocken (PA,USA), 2013.

[51] A. Abdulmatin, W. Tangchirapat, and C. Jaturapitakkul, "An investigation of bottom ash as a pozzolanic material," *Construction and Building Materials*, vol. 186, pp. 155-162, 2018/10/20/ 2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.07.101.

[52] M. Cheriaf, J. C. Rocha, and J. Péra, "Pozzolanic properties of pulverized coal combustion bottom ash," *Cement and Concrete Research*, vol. 29, no. 9, pp. 1387-1391, 1999/09/01/ 1999, doi: https://doi.org/10.1016/S0008-8846(99)00098-8.

[53] S. Oruji, N. A. Brake, L. Nalluri, and R. K. Guduru, "Strength activity and microstructure of blended ultra-fine coal bottom ash-cement mortar," *Construction and Building Materials*, vol. 153, pp. 317-326, 2017/10/30/ 2017, doi: https://doi.org/10.1016/j.conbuildmat.2017.07.088.

[54] J. R. a. T. R. Abdus Salaam Cadersa, "Assessing the Durability of Coal Bottom Ash as Aggregate Replacement in Low Strength Concrete " *Journal of Emerging Trends in Engineering and Applied Sciences (JETEAS)*, vol. 5, no. 5, pp. 344-349, 2014.

[55] R. S. Singh, "Compressive strength, drying shrinkage, and chemical resistance of concrete incorporating coal bottom ash as partial or total replacement of sand.," *construction and Building Materials*, vol. 68, pp. 39-48, 2014.

[56] N. M. Sigvardsen and L. M. Ottosen, "Characterization of coal bio ash from wood pellets and low-alkali coal fly ash and use as partial cement replacement in mortar," *Cement and Concrete Composites*, vol. 95, pp. 25-32, 2019/01/01/ 2019, doi: https://doi.org/10.1016/j.cemconcomp.2018.10.005.

[57] B. E. 196-1:2005, "Methods of testing cement - part 1: determination of strength.," 2005.

[58] A. I. C311-C311M, "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete," pp. 204-212, 2005.

[59] H. K. Kim and H. K. Lee, "Hydration kinetics of high-strength concrete with untreated coal bottom ash for internal curing," *Cement and Concrete Composites*, vol. 91, pp. 67-75, 2018/08/01/ 2018, doi: https://doi.org/10.1016/j.cemconcomp.2018.04.017.

[60] H. Kurama, İ. B. Topçu, and C. Karakurt, "Properties of the autoclaved aerated concrete produced from coal bottom ash," *Journal of Materials Processing Technology*, vol. 209, no. 2, pp. 767-773, 2009/01/19/ 2009, doi: https://doi.org/10.1016/j.jmatprotec.2008.02.044.

[61] H. Güllü, "A new prediction method for the rheological behavior of grout with bottom ash for jet grouting columns," *Soils and Foundations*, vol. 57, no. 3, pp. 384-396, 2017/06/01/ 2017, doi: https://doi.org/10.1016/j.sandf.2017.05.006.

[62] S. B. Park, Y. I. Jang, J. Lee, and B. J. Lee, "An experimental study on the hazard assessment and mechanical properties of porous concrete utilizing coal bottom ash coarse aggregate in Korea," *Journal of Hazardous Materials*, vol. 166, no. 1, pp. 348-355, 2009/07/15/ 2009, doi: https://doi.org/10.1016/j.jhazmat.2008.11.054.
[63] X. Gong, T. Wu, Y. Qiao, and M. Xu, "In Situ Leaching of Trace Elements in a Coal Ash Dump and Time Dependence Laboratory Evaluation," *Energy & Fuels*, vol. 24, no. 1, pp. 84-90, 2010/01/21 2010, doi: 10.1021/ef9005115.
[64] P. D. Trifunovic, S. R. Marinkovic, R. D. Tokalic, and S. D. Matijasevic, "The effect of the content of unburned carbon in bottom ash on its applicability for road construction," *Thermochimica Acta*, vol. 498, no. 1, pp. 1-6, 2010/01/20/ 2010, doi: https://doi.org/10.1016/j.tca.2009.10.022.

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