Exploring the Potential of CFBC Ash as Sustainable Building Material: A Review

Varsha Parmar[1,2,*], Prabha Padmakaran[1,2], Mohd. Akram Khan[1,2]

[1]CSIR-Advanced Materials and Processes Research Institute, Hoshangabad Road, Bhopal 462026 (M.P.), India
[2] Academy of Scientific and Innovative Research (AcSIR), Ghaziabad-201002, India

Volume 2, Issue 1, February 2025
Received:15 February, 2025; Accepted: 26 February, 2025
DOI: http://doi.org/10.63015/2e-2456.2.1

*Correspondence Author Email: varshaparmar.vp15@gmail.com

Abstract: Increasing use of CFBC technology for combustion of petroleum coke and other low calorific fuel offers high fuel efficiency and reduced coal utilization. India being the second largest ash producer in the world including petroleum coke fly ash with annual generation of 1,00,000 Metric Tons in an oil refinery located in Madhya Pradesh, India. The demand for its proper utilization and management is going up day-by-day. Coupled with the country's growing population and expanding infrastructure, the demand for construction materials is also increasing. The production of conventional material results in substantial CO_2 emission. Previous studies have discussed application of CFBC ash as cement (OPC, calcium sulphoaluminate, magnesium oxysulphate), concrete (AAC, RCC, NAAC), solid waste based zero cement binder (fly ash replacement of portland cement, AAC, magnesium sulphate cement, aggregates) have been discussed. However, challenges associated with CFBC ash are its porous and loose morphology, high water requirement, self- cementitious property and expansibility, which limits its potential uses and pose substantial challenges to human society. This review is focused on generation of CFBC ash, characterization of CFBC ash and advancement in processing techniques with focus on current and potential applications via waste management for industrial and societal benefits particularly for use in construction industry.

Keywords: CFBC Ash; Waste Management; Building Material; Societal Benefit; Sustainable Development

1.0 Introduction:

Global coal consumption is projected to rise by over 50% by 2030 and developing countries like India are likely to show an increase of more than 97% [1,2]. Due to this reason, coal gangue, sub-bitumen, lignite, peat, petcoke and other low-grade fuel are also used as coal substitute in thermal power stations which results in excessive emissions of CO_2, SO_2, and NOx which pose serious risk to human, plants and animal health and limit the sustainable ecological development [3]. Hence, CFBC technology is gaining popularity as it effectively processes a blend of low-grade fuels with diverse quality, composition and moisture levels. Within the boiler, limestone is added for in-situ desulfurization [4] and sand bed is suspended with the fuel by high-velocity air stream under fluidization. The bed material plays crucial role in enhancing heat transfer and minimizing temperature gradient confirming optimal turbulence at operating temperature between 700–900°C. This makes CFBC technology highly efficient and environment friendly [5,6]. The use of CFBC technology has increased globally due to low combustion temperature, reduced pollutant emissions, broad fuel compatibility, effective combustion and high desulfurization efficiency [7] which results in generation of CFBC ash. The residual CFBC ash that is discharged in large quantities is an important issue to consider as it can cause severe environmental pollution and ecological damage. Additionally, long-term storage of the ash can contaminate groundwater and soil quality [8]. Therefore, utilization of CFBC ash is very crucial for environmental protection and sustainable development.

Reported literature has detailed about utilization of CFBC ash, its physico-chemical characteristics and its present and future application with focus on utilization of CFBC ash in building materials or construction industry [5,9-12]. As reported in literature, author has reviewed various potential application of CFBC ash in agriculture, construction materials, adsorbent materials, waste stabilization and also addressed the limitations associated with CFBC ash [5]. Another author provided the comprehensive review of coal fly ash by detailing its generation, physico-chemical properties, global hazards and summarizing by present and future applications along with their advantages and disadvantages [13]. Previous articles focused on utilization of CFBC ash as construction material and related issues. This review aims to bridge the gap by examining recent advancements in processing techniques and focusing on existing and future applications including its utilization in the construction sector.

1.1 Generation of CFBC Ash:

The global annual generation of fly ash consisting of both pulverized coal combustion (PCC) and circulating fluidized bed combustion (CFBC) were reported as 750 million tons per annum (MTPA) in 2012 which increased to 904 MTPA by 2020 [14] whereas in India, the total fly ash (PCC and CFBC) production has increased from 83 MTPA in 2002 to 228 MTPA by 2020 marking nearly 175% increase during the last 18 years [15]. The future projections of ash generation will reach between 300 and 400 MTPA by 2025. The annual generation of petcoke fly ash from the Oil Refinery located in Madhya Pradesh is around 1,00,000 metric tons per annum which includes 70,000 metric tons per annum of petcoke fly ash (PCFA) and 30,000 metric tons per annum of Bed Ash (BA).

India has the third largest coal-power generating capacity in the world, providing for more than 70% of the total power demand in the country. Growing coal based power generation backed by domestic coal demand will further boost ash generation over the next decade. Even with the latest 83% ash utilization rate mainly going into cement, mine-filling/land-filling, bricks, blocks, tiles, infrastructure and concrete, around 17% of the annual ash generation (about 38 million tons) goes unutilized and is disposed into ash ponds/dykes and more than 1.6 billion tons of legacy ash is lying in ponds/dykes across the country.

2.0 Characterization of CFBC Ash:

The knowledge of detailed physico-chemical characterization of CFBC ash plays an important role for its disposal and utilization in scientific manner. The properties of CFBC ash are mainly determined by combustion condition and type of fuel used. Although CFBC boilers offer considerable fuel flexibility, most CFBC ash originates from thermal power plants that use coal or a blend of coal with other low-grade fuels, biomass, municipal solid waste and petcoke. This review mainly focuses on CFBC ash derived from different types of coal blended with petroleum coke.

2.1 Physico- Chemical Characterization:

The colour of CFBC ash is generally greyish in colour and varies from blackish to brownish colour based on the raw material used. The addition of limestone results in relatively light colour. The higher unburnt carbon content was responsible for darker colour of CFBC ash. The reddish-brown colour of CFBC ash indicates the presence of iron content mainly hematite

[16]. The CFBC ashes possess broad particle size distribution with an average particle size ranging from 12.4 -43µm [17-19]. The fineness of ash mainly depends on type of fuel, fuel combustion ratio and combustion process. In CFBC boiler, pulverized coal gets properly fluidized with bed material followed by crushing, combustion and heat exchange which results in more fineness in CFBC ash [20] that around 53% of CFBC ash particles have particle size distribution between 0.1 to 16 µm. The specific gravity and Blain fineness of CFBC ash were found in the range of 2.50-2.80 and 2880– 3050 cm^2/g respectively [21-24] whereas the BET surface area of CFBC ash are observed in the range of 2.5– 67m^2/g [17,24]. The CFBC ash usually has high pH which makes it alkaline in nature which is due to the presence of high calcium content.

The chemical composition of CFBC ash mainly consist of SiO_2, Al_2O_3, SO_3, CaO, Fe_2O_3 with minor contents of Na_2O, K_2O and MgO as summarized in **Table 1** which are main elemental oxides in CFBC ash as reported in literature. Generally, CFBC ash generated by desulphurization process has high content of SO_3 and CaO and has almost linear proportionality. The observed linear increase in sulfur content with calcium content is attributed to the desulfurization process. i.e., addition of limestone/dolomite in- situ for adsorption of emitted SO_2 in boiler. The loss on ignition (LoI) is generally higher in CFBC ash which contributes to more unburnt carbon, sulfur-binding agents and sulfur-binding products in ash which is due to low combustion temperature of CFBC boiler as compared to other boilers. Apart from this, fluidization rate of CFBC also influences loss on ignition. As fluidization rate increases, amount of unburnt carbon gradually increases. Hence decarbonization treatment is performed on CFBC ash with higher LoI [25]. The content of SiO_2, SO_3, CaO and LoI varies significantly due to factors such as difference in combustion condition and type of fuel used [26] (coal, petcoke and other fuel blend with coal) and quantity of desulphurizing agent used.

Table:1 Elemental Oxides in CFBC Ashes [27-48]

Metal Oxides	Minimum (wt%)	Maximum (wt%)
CaO	1.40	56.80
SiO_2	0.22	53.50
Al_2O_3	0.10	50.98
SO_3	0.50	40.60
Fe_2O_3	0.10	27.9
MgO	0.15	7.10
Na_2O	0.10	1.17
K_2O	0.34	0.55
LoI	2.75	14.70

1

2.2 Mineralogical Content:

The key mineralogical phases found in CFBC ash are Anhydrite ($CaSO_4$), Portlandite ($Ca(OH)_2$), Quartz (SiO_2), Calcite ($CaCO_3$), Quicklime (CaO) and Hematite (Fe_2O_3) [47-51]. CFBC ash typically has higher proportion of crystalline phases due to lower combustion temperature used in CFBC boilers compared to other types of boilers.

The proportions of amorphous and crystalline phases in CFBC ash were determined using X-Ray Diffraction (XRD). The crystalline phases range between 25% to 63% while the amorphous content of CFBC ash was estimated to be between 57% to 82% [14]. Quicklime and Anhydrite are also found as CFBC boilers use limestone for desulfurization. Quartz is originally present in the fuel and Calcite is produced by reaction between Lime with CO_2 in the air. Portlandite is formed when free lime of CFBC ash comes in contact with air and react with water vapour during storage whereas Calcite and Lime is formed due to addition of desulphurization agent during the combustion in CFBC boiler [20,47,10].

The combustion of low grade coal in CFBC boiler leads to increase in SO_2 emission which results in increase in lime content. It is reported that higher levels of SO_3 and lime contribute positively to enhance self-cementitious strength [11]. It is also confirmed from previous studies that CFBC ash contain Calcium, Aluminum and Silicon as reactive component and the hydration product of these components lead to formation of Portlandite and Ettringite in the initial stage and the layer gets converted into Calcium Silicate Hydrate (C-S-H) and Gypsum [20,47,49]. It was also noticed that fly ash from various Thermal Power Plants vary in properties due to different fuel blending ratio and different combustion conditions.

2.3 Morphological Properties:

The morphology of CFBC ash mainly consists of irregular block or rod-shaped particles that are flaky, angular and loose, porous surface [47,50-52]. The main reason for irregular shape is combustion temperature of CFBC boiler which is in range of 700-900°C. This temperature range could not melt irregularly shaped ash particles into spherical shapes resulting in irregular microstructure of unburnt carbon particles, Anhydrite, Calcite, Lime [18] in CFBC ash. Furthermore, Limestone degradation and CO_2 emission during the reaction phase might cause surface loosening [20,53,54]. The high water requirement of CFBC ash along with its loose and porous structure prevents it from being used in accordance with fly ash treatment procedures. Hence, CFBC ash has greater water requirement for normal consistency as compared to Ordinary Portland Cement.

3.0 CFBC Ash as Building Material:

The generation of large amounts of CFBC ash causes serious problems in terms of its safe disposal and storage as it has negative impact on environment like ground water contamination, environmental pollution occupying large space including farmlands thus wasting resources. Therefore, proper management and potential utilization of CFBC ash is very important to protect environment and sustainable development. Various researchers have reported and discussed the application of CFBC ash as cement substitute material in Ordinary Portland Cement, Magnesium Oxysulphate and Calcium Sulfoaluminate in concrete like Autoclave Aerated Concrete, Non-Autoclave Aerated Concrete, Roller Compacted Concrete. Apart from this, CFBC ash is used as zero cement binder along with various industrial solid wastes like Coal Fly Ash, Blast Furnace Slag, Tailings etc. Currently, broad areas of application of CFBC ash in construction application include Roller Compacted Concrete, Light Weight Aggregate/Foam Concrete, Portland Pozzolana Cement replacement, Concrete, Bricks and Geopolymer. The key contributions by various researchers on the application of CFBC ash in civil infrastructure materials are summarized in **Table 2**.

Table 2: Summary of Applications of CFBC Ash as Building Material

No.	Application	Raw Material	Additives	Properties	Ref.
1.	Cement	CFBC Ash	OPC, Class F fly	Water absorption,	[55-59]

			ash, GBF slag, limestone filler, Portland cement, commercial gypsum	Compressive, tensile, flexural strength, elasticity modulus, elasticity modulus, particle size, XRD, SEM.	
2.	Zero Cement Binder	CFBC Ash	Fly ash, ground granulated blast furnace slag (GGBS), silica fume, recycled aggregates	Compressive strength, heat of hydration, initial - final setting time, thermal analysis, microstructure study.	[40,41,60-67]
3.	Autoclaved Aerated Concrete	CFBC Ash	Fly ash, cement, superplasticizer (polycarboxylate), lime	Dry density, pore structure, compressive and specific strength and hydration products.	[49,68-71]
4.	Non-Autoclaved Aerated Concrete	CFBC Ash	Aluminate cement/ Portland cement/ PCC fly ash, cement, phosphogypsum	Compressive strength, morphological, volume stability, drying shrinkage, frost resistance and thermal conductivity.	[72-75]
5.	Roller Compacted Concrete	CFBC Ash	Cement, river sand, OPC, coarse aggregates, gravel	Compressive, Flexural Strength, setting time, sulphate resistance, density, thermal conductivity, microstructural analysis.	[76,77]
6.	Light Weight Aggregate	CFBC Ash	Glass powder, perlite tailing powder, bentonite, calcium carbonate, oil-contaminated drill cuttings (OCDC), quicklime.	Cylinder strength, water absorption apparent density, softening coefficient, bulk density.	[78,79]
7.	Concrete	CFBC Ash	Cement, river sand, coarse aggregate, gravel, slag.	XRD, Thermal analysis, Compressive and Flexural Strength.	[40,80]
8.	Alkali Activator/ Geopolymer	CFBC Ash	Sodium Hydroxide, Sodium Meta Silicate, Metakaolin.	Compressive Strength, Microstructure, FTIR, Physico chemical Properties.	[81-85]

3.1 Ordinary Portland Cement:
Conventionally, fly ash is known for its effectiveness as mineral admixture and has been extensively utilized in Portland

Pozzolana Cement. Similarly, CFBC ash has been used as a mineral additive in Portland Cement. Research on its effects on physico- mechanical properties of cement-based composites has emerged as key area of research for its resource utilization in building materials. The findings of few researchers in terms of properties reported that expansion of CFBC ash reduces shrinkage of cement mortar [55] and another study concluded that CFBC ash can increased the hydration rate of Tricalcium Silicate and enhances the early formation of Ettringite (AFt) and thus results in improvement of mechanical properties of cement [56]. It is highlighted how activators can enhance the hydration process of cement by generating Portlandite ($Ca(OH)_2$) which in turn activates the pozzolanic reaction of CFBC ash resulted in formation of Calcium Silicate Hydrate (C-S-H) gel with lower Aluminum to Silicon ratio positively influencing cement hydration and improving its early strength [57]. A study conducted in 2019 has explored that grinding CFBC ash to a fineness comparable to cement enhances its pozzolanic activity making it a suitable replacement for cement clinker [58]. It was also reported in the literature that when CFBC ash is combined with other materials, it leads to the formation of significant quantities of Ettringite and Silicates. This reaction driven by sulfate ions and free lime results in reducing shrinkage/self-shrinkage in the material [59].

3.2 Zero-Cement Binder:

The production of one ton of cement results in release of 800 kg of CO_2 significantly contributing to global atmospheric pollution and emissions of greenhouse gas. The cement industry accounts for 8% of global CO_2 emission [60]. As a result, the development of alternative binders involves using solid waste materials like coal fly ash, CFBC ash and GGBFS which has emerged as a key area of investigation in the area of solid waste and construction materials owing to its efficacy as supplementary and alternative cementitious material. It is distinguished by its high utilization efficiency and lower carbon emissions associated with its production process. Numerous researchers have investigated the development of zero-cement binders by utilizing various forms of solid waste.

Previous study demonstrated that CFBC ash with varying free lime content can be used to develop zero- OPC binders. These binders form hydration products similar to conventional cement. Free-CaO content ranges from 9.0% to 17.0% which to ensures desirable setting characteristics and compressive strength along with pre-hydration controlled free-CaO content and improved performance. Mineral admixtures like fly ash, silica fume and GGBFS further enhanced strength and durability [61]. Researchers has developed an eco-binder by combining Circulating Fluidized Bed Combustion Fly Ash (CFBCFA) with Ground Granulated Blast Furnace Slag (GGBFS) without incorporating Ordinary Portland Cement or alkaline activators. The hydration products formed were included Ettringite, Calcium-Silicate-Hydrate and Aluminum-modified Calcium Silicate Hydrate gel. The maximum achieved compressive strength after 28 days was 75 MPa [62]. Prior to this study, it is also investigated that mortars (SCA) made from CFBC fly ash (CA) and slag (S) exhibited good sulfate resistance and strength reduction restricted to approximately 15% or less [41]. Additionally, it is also demonstrated that the eco-binder SCA paste achieved appropriate setting time and adequate strength with compressive and tensile strengths of 80 MPa and 4.6 MPa respectively at 28 days. The hydration products includes Ettringite, C-S-H and C-S-A-H which formed a dense, self-cementitious microstructure leading to lower ultimate drying shrinkage compared to Ordinary Portland Cement paste[40]. Study conducted in 2019 found that adding brown coal fly ash to GGBFS accelerates early hydration, reduces setting time and increases early compressive strength. Additionally, increasing the fly ash content resulted in a 20% reduction in setting time and a 22% improvement in compressive strength [63].

Few researchers examined a ternary blended no-cement mortar consist of Class F Fly Ash, GGBFS and CFBC Ash. They found that while the mortar demonstrated good durability and heat resistance below 400°C both its weight and compressive strength significantly decreased at temperatures exceeding 600°C. Strength loss is minimal up to 400°C and its weight reduction occurs at 800°C in a study conducted in 2018 [64]. Study carried out in 2017 investigated zero-cement mortar made from CFBC ash, Blast Furnace Slag and recycled aggregates achieving up to 50 MPa compressive strength after 91 days with an optimal mix of CFBC 75:25. The mortar exhibits excellent durability, including enhanced resistance to chloride diffusion, frost, carbonation and sulfuric acid [65]. Some authors reutilized waste co-fired fly ash through CFBC boiler as an alkali activator in combination with GGBFS to create an eco- friendly binder. The reported best mix i.e, 30% CFFA and 70% GGBS attained 31.43 MPa compressive strength which is 72.4% of the Ordinary Portland mortar strength. This results in the formation of C–S–H and C–A–S–H gels resulting from the reaction between CaO with H_2O, SiO_2 and Al_2O_3 [66] whereas some explored the use of CFBC bottom ash in controlled low strength materials (CLSM). Laboratory tests on various mixture proportions showed that incorporating fly ash and GGBS with bottom ash improves flowability, setting time, compressive strength and water absorption [67]. These findings indicate that secondary products like fly ash, ground-granulated blast furnace slag, silica fume and recycled aggregates can be effectively utilized in promoting sustainable development. It is suggested that CFBC ash-based zero-OPC binders can be used as sustainable alternative to traditional cements for reducing CO_2 emissions and for utilizing industrial waste.

3.3 Autoclaved Aerated Concrete:

Autoclaved aerated concrete (AAC) is a lightweight precast building material that contains air bubbles throughout its structure, giving it a cellular composition. Some researchers tried to use CFBC ash for making AAC and suggested that addition of CFBC ash can bring several benefits to AAC. In previous study conducted by few researchers indicates that feasibility of substituting up to 50% fly ash in cementitious materials without experiencing a substantial reduction in compressive strength. Microstructural analysis validated the integration of aluminum ions into the C-S-H phase with consistent presence of crystalline Tobermorite [68]. In 2015, it has been reported that incorporation of CFBC ash in AAC with the addition of superplasticizer Polycarboxylate (PCE) can significantly influence the material's properties. Optimal PCE content and Water to Powder (W/P) ratios are critical for maintaining desirable rheological properties and effective gas-foaming which in turn affect the porosity and overall performance of the AAC [49]. The utilization of CFBC ash in AAC is feasible and can lead to improved properties and the density of AAC with CFBC ash was slightly lesser as compared to traditional AAC indicating potential benefits in terms of lightweight construction materials as reported in study conducted in 2021[69]. Further, microstructural analysis revealed changes in the pore structure and hydration products suggesting alterations in the concrete's internal structure.

It was also concluded by researchers that the use of 16wt% lime as a partial replacement of cement in AAC results in improvement of compressive strength with presence of Tobermorite crystals microstructure which contributes in property improvement [70]. However, beyond this, the microstructure of AAC is adversely affected. Hence, previous studies suggest that creating aerated concrete serves as an optimal approach for recycling CFBC ash and producing concrete. Previous study addressed the challenge of high water absorption in CFBC ash and investigated its feasibility in preparing AAC concrete which indicated that the water-reducing effect of superplasticizers enhance the slurry's rheology to synchronize with the gas generation rate of aluminum powder, thereby optimizing pore structure, reducing the number of harmful pores (<50 nm) and improving product strength [71]. High water content introduces numerous uneven macropores whereas low water content hampers cement hydration, reducing the formation of C-S-H gel and Tobermorite. A balanced combination of water content and water-reducing agent improves AAC strength without significantly altering bulk density.

3.4 Non-Autoclaved Aerated Concrete:

Non-Autoclaved Aerated Concrete (NAAC) is a type of lightweight concrete that is not cured in an autoclave. Aerated concrete typically comprises of cement, lime, gypsum, sand and small amount of pore-forming agent i.e., aluminum powder on reaction with lime generating hydrogen gas and various fine bubbles that are evenly distributed throughout the matrix [72,73]. This results in lightweight, porous concrete with good thermal insulation properties and fire resistance. In comparison to traditional autoclaved aerated concrete, non-autoclaved aerated concrete offers significant advantages in streamlining the manufacturing process and lowering production costs. Currently, CFBC ash has been utilized in the production of both AAC and NAAC.

Research study performed in 2013 identified the Coal Fly Ash (CFA) as the primary raw material for NAAC. The study involved rheological, physical, chemical, microstructure and mechanical analysis to assess the impact of raw materials on NAAC properties. The optimal composition was found to be 65.5% CFA, 22% cement and 10% lime with an ideal particle size range of CFA between 9.6μm and 23.9μm and the key minerals were needle shaped like Ettringite and floccular pattern of C–S–H [74]. Few researchers have also explored the utilization of CFBC ash to prepare foam concrete with 60℃ steam curing for 24 hours. The optimal mix was found to be 70% CFA, 8% Quicklime, and 2% Aluminate cement. The addition of Aluminate cement or Quicklime accelerated the setting and hardening process of the slurry. For better compressive strength, finer CFA and lower w/s ratio were preferred. The resulting foam concrete exhibited good compressive strength, resistance to frost and thermal conductivity [75].

3.5 Roller Compacted Concrete:

Roller-compacted concrete (RCC) is a type of concrete that is laid and compacted using machinery similar to that employed for asphalt pavement. Few authors explored the preparation of RCC using CFBC ash through replacement of fine aggregates. Author reported that replacement of CFBC ash with 5% as fine aggregate at 75g/cm^2 of roller compaction pressure increased water absorption and reduced initial surface absorption, improved compressive strength, tensile strength and sulphate resistance of RCC [76]. In 2019, other author has reported that 10% CFBC ash replacement as fine aggregates and rolling pressure of 100g/cm^2 enhances the development of flexural strength, reduces the initial and the final setting time by 30%-60% and 16%-20% respectively [77]. Based on SEM and XRD results, it was confirmed that increasing the amount of CFBC ash as a substitute for fine aggregate led to an improvement in the density of C-S-H gel and gradual increase in the content of Portlandite.

3.6 Aggregates:

Research undertaken in 2020 found that Calcium Sulfate in CFBC ash acts as a foaming and fluxing agent promoting the formation of vitrified surface and porous cellular structure during sintering process. This in turn, leads to a substantial decrease in water absorption and apparent density of the Ceramsite. Optimized process yielded 700-grade lightweight CFBC ash Ceramsite with 50–70% content of CFBC ash and cylinder strength of 5.3MPa [78]. In the same year other authors has investigated the feasibility of co-mechano-chemical treatment of CFBC ash, oil-contaminated drill cuttings (OCDC) and quicklime to develop non-sintered lightweight aggregates and reported that light weight aggregates exhibit high cylinder compressive strength of 17.87 MPa and low water absorption rate of 6.28%. These properties were achieved under optimal conditions of water addition, steam-curing (60°) and steam- curing time (12hr). The co-mechano-chemical treatment effectively enhanced the pozzolanic activity of CFBC ash thereby contributed in enhancement of strength [79].

3.7 Concrete:

Several researchers have examined the application of CFBC ash for the preparation of roller compacted concrete (RCC). It is dry and stiff form of concrete which doesn't have slump. Several studies have explored the utilization of CFBC ash in various type of concrete which are summarized in **Table 2.** They investigated CFBC ashes from coal combustion at three thermal power plants using them as cement binder additives in concrete with 20% to 30% weight substitution and observed the decrease in Portlandite content and moderate alterations changes in Ettringite content in CFBC ash incorporating cement pastes as confirmed through XRD and thermal analysis. The study concluded that addition of CFBC ash increases C–S–H gel and crystalline Ettringite content and also enhances hydration products without significantly altering the qualitative phase composition of cement paste [80].

3.8 Geopolymer:

Geopolymers were initially introduced by French Scientist Joseph Davidovits in the late 1970s to describe inorganic polymers formed by the geopolymerization process. The study conducted in 2011 tested the potential application of CFBC ash in ceramic tile manufacturing through the sintering technique. Specimen were moulded using extrusion fired at 1050°C and tested for microstructure and physical properties. Various properties were evaluated for plasticity, water absorption and mechanical strength [86]. Later in 2020, another author studied the impact of partially substituting Pulverized Coal Combustion (PCC) fly ash with Circulating Fluidized Bed Combustion (CFBC) ash in alkali-activated materials utilization different molar concentration (4M, 5M, and 6M) of Sodium Hydroxide along with Sodium Silicate solution. The research revealed strong correlation between the compressive strength and Sodium Hydroxide molarity of CFBC ash based alkali-activated materials with the relation that higher molarity resulting in greater compressive strength[82].

In 2010, few authors reported that low-reactive CFBC ash can be effectively used as a raw material for geopolymer production by enhancing their reactivity through an alkali fusion process and balancing the Na/Al ratio with an additional Aluminosilicate source such as high-reactive Metakaolin (MK) with dense and homogeneous microstructure [83]. The higher alkali activator ratio (i.e. sodium silicate to sodium hydroxide) enhanced compressive strength and produced dense, homogeneous composites, while lower ratio resulted in weaker materials with more Calcium Hydroxide [84]. It was also investigated that addition of high calcium coal based ash to grinding CFBC ash enhanced the properties of CFBC ash based geopolymer composite as PCC fly ash is rich in glassy phases which easily released Si and Al ions when treated with alkali solution and hence facilitating the formation of a linking network in geopolymeric composites [85].

4.0 Conclusions:

Based on the extensive research on characterization and utilization of CFBC ash, the study highlights its wide- ranging potential application across various sectors. Among these the most promising areas of application with lot of encouraging research have been reported in its use in cement and non- cementitious building materials including aerated concrete, geopolymers, synthetic light weight aggregates and other non- structural construction materials. Key findings from this research include:

1. CFBC ash shows significant potential as mineral admixture in Portland cement offering several advantages which includes the acceleration of hydration, reduction of shrinkage, enhancement of pozzolanic activity and early strength improvement. Research findings indicate that CFBC ash can lessen cracking by minimizing shrinkage, promote hydration of Ettringite (Aft) and Tricacium Silicate(C_3S) for early strength and to facilitate pozzolanic reactions through activators. It can also be serves as an effective clinker replacement after mechanical activation.

2. CFBC ash and other industrial by-products such as fly ash, GGBS and recycled aggregates is a viable alternative to conventional portland cement. These materials significantly reducing CO_2 emissions. According to research, CFBC ash based zero cement binders have excellent durability, compressive strength and environmental resistance. These binders create hydration products that are similar to conventional cement however perform better and making them a viable option for sustainable building materials.

3. CFBC ash shown its capability to replace conventional ash without cement compromising strength in autoclaved aerated concrete (AAC). It contributes to improves pore structure, reduces density and formation of beneficial hydration products like Tobermorite. Optimal use of superplasticizers and water-to-powder ratio is important for maintaining desirable properties. As result, CFBC ash serves as a valuable material for lightweight, durable and sustainable AAC thereby promoting industrial waste recycling in construction.

4. CFBC ash effectively replaces fine aggregates in roller-compacted concrete (RCC) enhancing its compressive, flexural strength, tensile strength and sulfate resistance while reducing initial surface absorption and setting times. Optimal replacement levels and compaction pressures further improve C-S-H gel density and Portlandite content and enhancing overall RCC's performance and sustainability. It also acting as foaming agent thus improves lightweight aggregates by reducing density and water absorption. Co-mechano-chemical treatment increases its pozzolanic activity and strength along with sustainable aggregates like Ceramsite.

5. The manufacturing of geopolymer from CFBC ash exhibits considerable promise. The compressive strength of alkali-activated materials is significantly influenced by the sodium hydroxide concentration with higher concentrations producing superior outcomes. Furthermore, alkali fusion can be used to activate low-reactive CFBC ash for geopolymerization, specially when paired with aluminosilicates like metakaolin, resulting in dense, high-strength composites.

5.0 Future Research Prospects:

It has been noticed that despite of extensive research has been done on CFBC ash for its application in various field these is always a scope for improvement. Some challenges associated while using CFBC ash in construction applications which needs to be optimize and overcome like water-cement ratio, curing conditions and blending ratios to maximize the potential utilization of CFBC ash. Additionally, more research needs to be done to enhance strength, durability and workability. Further, the application of CFBC ash through geopolymerization can be more explored. There is a great variation in results due to varying composition of ash and there is no standard available till date which could also be explored and optimized to ensure consistent performance in various applications.

Acknowledgement:
The authors are grateful to Prof. Avanish Kumar Srivastava, Director, CSIR-AMPRI, Bhopal for granting the permission to publish this work.

References:

1. Cheng Z, Cheng Z, Hou H, Han T, Liu L. Research on the expansion characteristics and compressive strength of mortars containing circulating fluidized bed combustion desulfurization slag. Advances in Materials Science and Engineering. 2018;2018.
2. Jatav PP, Tajane SP, Mandavgane S, Gaidhani S. A process of carbon enrichment of bottom slag ash for value-added applications. Journal of Material Cycles and Waste Management. 2019;21:539-46.
3. Zhai M, Guo L, Sun L, Zhang Y, Dong P, Shi W. Desulfurization performance of fly ash and $CaCO_3$ compound absorbent. Powder Technology. 2017;305:553-61.
4. Petr B, Hlincik T. Enrichment of Limestone Used in the Desulphurisation of Fluidised-Bed-Boiler Flue Gases. Adsorption Science & Technology. 2021;2021:1-9.
5. Ohenoja K, Pesonen J, Yliniemi J, Illikainen M. Utilization of fly ashes from fluidized bed combustion: A review. Sustainability. 2020;12(7):2988.
6. Wang L, Quan H, Li Q. Effect of solid waste-petroleum coke residue on the hydration reaction and property of concrete. Materials. 2019;12(8):1216.
7. Chen J, Lu X. Progress of petroleum coke combusting in circulating fluidized bed boilers—a review and future perspectives. Resources, conservation and recycling. 2007;49(3):203-16.
8. Fu X, Li Q, Zhai J, Sheng G, Li F. The physical–chemical characterization of mechanically-treated CFBC fly ash. Cement and Concrete Composites. 2008;30(3):220-6.
9. González A, Navia R, Moreno N. Fly ashes from coal and petroleum coke combustion: current and innovative potential applications. Waste Management & Research. 2009;27(10):976-87.
10. Patel A, Basu P, Acharya B. An investigation into partial capture of CO2 released from a large coal/petcoke fired circulating fluidized bed boiler with limestone injection using its fly and bottom ash. Journal of environmental chemical engineering. 2017;5(1):667-78.
11. He P, Zhang X, Chen H, Zhang Y. Waste-to-resource strategies for the use of circulating fluidized bed fly ash in construction materials: A mini review. Powder Technology. 2021;393:773-85.
12. Jia G, Wang Y, Yang F. A Review on the Application of Circulating Fluidized Bed Fly Ash in Building Materials. Advances in Materials Science and Engineering. 2022;2022.
13. Yao, Z. T., Ji, X. S., Sarker, P. K., Tang, J. H., Ge, L. Q., Xia, M. S., & Xi, Y. Q. (2015). A comprehensive review on the applications of coal fly ash. *Earth-science reviews*, *141*, 105-121.
14. Pei, J et al, (2023). Harnessing fluidised bed combustion fly ash as a potential green binder: Origin, characteristics, mechanisms and products properties. Next Materials, 1(2), 100015
15. Central Electricity Authority, CEA annual report ⟨https://cea.nic.in/annual-report/?lang=en⟩, 2021 (accessed 20 October 2022).
16. Ning M, Wang Z, Qian J, Tang S. Characteristics of fluidized bed coal

combustion fly ash and slag and its adaptability with current standards. Bulletin of the Chinese Ceramic Society. 2019;38(3):688-93.
17. Lee S-H, Kim G-S, Lee S-H, Kim G-S. Self-cementitious hydration of circulating fluidized bed combustion fly ash. Journal of the Korean Ceramic Society. 2017;54(2):128-36.
18. Zhou W, Yan C, Duan P, Liu Y, Zhang Z, Qiu X, et al. A comparative study of high-and low-Al2O3 fly ash based-geopolymers: The role of mix proportion factors and curing temperature. Materials & Design. 2016;95:63-74.
19. Paaver P, Paiste P, Liira M, Kirsimäe K. Mechanical activation of the Ca-rich circulating fluidized bed combustion fly ash: Development of an alternative binder system. Minerals. 2020;11(1):3.
20. Zhao J, Wang D, Hui F. Characterization and resource utilization of circulating fluidized bed ash of gangue power plant. China Mining Magazine. 2014;23(7):133-8.
21. Nguyen H-A, Chang T-P, Shih J-Y, Chen C-T, Nguyen T-D. Influence of circulating fluidized bed combustion (CFBC) fly ash on properties of modified high volume low calcium fly ash (HVFA) cement paste. Construction and Building Materials. 2015;91:208-15.
22. Chi M, Huang R. Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete. Cement and Concrete Composites. 2014;45:148-56.
23. Chindaprasirt P, Kasemsiri P, Poomsrisa-Ard S, Posi P. Fluidized bed coal-bark fly ash geopolymer with additives cured at ambient temperature. GEOMATE Journal. 2019;16(54):29-35.
24. Kang YH, Choi YC. Development of non-sintered zero-OPC binders using circulating fluidized bed combustion ash. Construction and Building Materials. 2018;178:562-73.
25. Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete Maochieh Chi, Ran Huang, Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete, Cement & Concrete Composites 45 (2014) 148–156
26. W.T. Lin, T.L. Weng, A. Cheng, S.J. Chao, H.M. Hsu, Properties of controlled low strength material with circulating fluidized bed combustion ash and recycled aggregates, Mater. 11 (2018) 715, https://doi.org/10.3390/ma11050715.
27. Mingkai Zhou et al., Study on hydration characteristics of circulating fluidized bed combustion fly ash (CFBCA), Build. Mater.(2020)
28. X. Xiao, H. Yang, H. Zhang, A. Junfu Lu, G. Yue, Research on carbon content in fly ash from circulating fluidized bed boilers, Energy Fuel 19 (2005) 1520–1525, https:// doi.org/10.1021/ef049678g
29. Pomykala, R. Properties of solidified fly ash suspension heated at high temperature. In Proceedings of the Thirtieth annual International Pittsburgh Coal Conference, Beijing, China, 15–18 September 2013; Curran: Norwich, UK, 2013; Volume 3, pp. 2449–2464.
30. González, A.; Moreno, N.; Navia, R.; Querol, X. Study of a Chilean petroleum coke fluidized bed combustion fly ash and its potential application in copper, lead and hexavalent chromium removal. Fuel 2010, 89, 3012–3021. [CrossRef]
31. Wang, Z.; Song, Y.; Li, B. An Attempt to Reduce Materials Cost of Autoclaved Aerated Concrete Production. Open Civ. Eng. J. 2016, 10.
32. Illikainen, M.; Tanskanen, P.; Kinnunen, P.; Körkkö, M.; Peltosaari, O.; Wigren, V.; Österbacka, J.; Talling, B.; Niinimäki, J. Reactivity and self-hardening of fly ash from the fluidized bed combustion of wood and peat. Fuel 2014, 135, 69–75.
33. Shen, Y.; Qian, J.; Zhang, Z. Investigations of anhydrite in CFBC fly ash as cement retarders. Constr. Build. Mater. 2013, 40, 672–678.
34. Dung, N.T.; Chang, T.-P.; Chen, C.-T.; Yang, T.-R. Cementitious properties

and microstructure of an innovative slag eco-binder. Mater. Struct. 2016, 49, 2009–2024.

35. Nguyen, H.-A.; Chang, T.-P.; Shih, J.-Y.; Chen, C.-T.; Nguyen, T.-D. Sulfate resistance of low energy SFC no-cement mortar. Constr. Build. Mater. 2016, 102, 239–243.

36. Chen, C.-T.; Nguyen, H.-A.; Chang, T.-P.; Yang, T.-R.; Nguyen, T.-D. Performance and microstructural examination on composition of hardened paste with no-cement SFC binder. Constr. Build. Mater. 2015, 76, 264–272.

37. Nguyen, H.-A.; Chang, T.-P.; Chen, C.-T.; Yang, T.-R.; Nguyen, T.-D. Physical-chemical characteristics of an eco-friendly binder using ternary mixture of industrial wastes. Mater. Constr. 2015, 65, 064.

38. Dung, N.T.; Chang, T.-P.; Chen, C.-T. Engineering and sulfate resistance properties of slag-CFBC fly ash paste and mortar. Constr. Build. Mater. 2014, 63, 40–48.

39. Dung, N.T.; Chang, T.-P.; Yang, T.-R. Performance Evaluation of an Eco-Binder Made with Slag and CFBC Fly Ash. J. Mater. Civ. Eng. 2014, 26, 04014096.

40. Dung, N.T.; Chang, T.-P.; Chen, C.-T. Circulating fluidized bed combustion fly ash-activated slag concrete as novel construction material. ACI Mater. J. 2015, 112, 105–114.

41. Nguyen, H.-A.; Chang, T.-P.; Shih, J.-Y.; Chen, C.-T.; Nguyen, T.-D. Engineering properties and durability of high-strength self-compacting concrete with no-cement SFC binder. Constr. Build. Mater. 2016, 106, 670–677.

42. Ohenoja, K.; Tanskanen, P.; Wigren, V.; Kinnunen, P.; Körkkö, M.; Peltosaari, O.; Österbacka, J.; Illikainen, M. Self-hardening of fly ashes from a bubbling fluidized bed combustion of peat, forest industry residuals, and wastes. Fuel 2016, 165, 440–446.

43. Huynh, T.-P.; Vo, D.-H.; Hwang, C.-L. Engineering and durability properties of eco-friendly mortar using cement-free SRF binder. Constr. Build. Mater. 2018, 160, 145–155.

44. Jozwiak-Niedzwiedzka, D. Estimation of chloride migration coefficient in air-entrained concretes containing fluidized bed combustion fly ash. Arch. Civ. Eng. 2012, 58, 25–38.

45. Papa, E.; Medri, V.; Landi, E.; Ballarin, B.; Miccio, F. Production and characterization of geopolymers based on mixed compositions of metakaolin and coal ashes. Mater. Des. 1980-2015 2014, 56, 409–415.

46. Wei-Ting Lin, Kae-Long Lin , Kailun Chen , Kinga Korniejenko, Marek Hebda and Michał Łach, Circulation Fluidized Bed Combustion Fly Ash as Partial Replacement of Fine Aggregates in Roller Compacted Concrete. Materials 2019, 12, 4204; doi:10.3390/ma12244204.

47. F. Li, J. Zhai, X. Fu, G. Sheng, Characterization of fly ashes from circulating fluidized bed combustion (CFBC) boilers cofiring coal and petroleum coke, Energy Fuel 20 (2006) 1411–1417, https://doi.org/10.1021/ef050377w.

48. G. Bernardo, A. Telesca, G.L. Valenti, F. Montagnaro, Role of ettringite in the reuse of hydrated fly ash from fluidized-bed combustion as a sulfur sorbent: a hydration study, Ind. Eng. Chem. Res. 43 (2004) 4054–4059, https://doi.org/10.1021/ ie030716d.

49. Y. Song, J. Qian, Z. Wang, Z. Wang, Self-cementing mechanism of CFBC coal ashes at early ages, J. Wuhan Univ. Technol-Mater. Sci. Ed. 23 (2008) 338–341, https://doi. org/10.1007/s11595-007-3338-9

50. Rajamma, R.; Ball, R.J.; Tarelho, L.A.C.; Allen, G.C.; Labrincha, J.A.; Ferreira, V.M. Characterisation and use of biomass fly ash in cement-based materials. J. Hazard. Mater. 2009, 172, 1049–1060.

51. X. Shan, Z. Ma, Y. Guo, and F. Cheng, “Study on characteristics of circulating fuidized bed pulverized fuel ash with diferent particle sizes,” Coal Science and Technology, vol. 46, no. 11, pp. 232–238, 2018.

52. Wu, T.; Chi, M.; Huang, R. Characteristics of CFBC fly ash and properties of cement-based composites with CFBC fly ash and coal-fired fly ash. Constr. Build. Mater. 2014, 66, 172–180.
53. K. He, Z. Lu, J. Li, and K. Song, “Comparative study on properties of circulating fluidized bed combustion ash and slag,” Journal of Wuhan University of Technology, vol. 36, no. 3, pp. 6–13, 2014.
54. J. Qian, Z. Zhang, H. Zheng, and Z. Wang, “Study on the varieties and distribution of sulfur minerals in CFBC ash/slag,” Journal of China Coal Society, vol. 38, no. 4, pp. 651–656, 2013.
55. Chen, J. Gao, Y. Yan, and Y. Liu, “Investigation of expansion properties of cement paste with circulating fluidized bed fly ash,” Construction and Building Materials, vol. 157, pp. 1154–1162, 2017.
56. H. A. Nguyen, T. P. Chang, J. Y. Shih, C. T. Chen, and T. D. Nguyen, “Influence of circulating fluidized bed combustion (CFBC) fy ash on properties of modified high volume low calcium fy ash (HVFA) cement paste,” Construction and Building Materials, vol. 91, pp. 208–215, 2015.
57. W. Zhao, T. Su, P. Zhang, and S. Zhao, “CFBC desulfurization ash cement early-age strength performance study,” Non-Metallic Mines, vol. 39, no. 1, pp. 67–70, 2016.
58. D. Carro-Lopez, B. Gonz ´ alez-Fonteboa, J. Eiras-L ´ opez, and ´ S. Seara-Paz, “Comparing circulating fluidized bed fly ash and limestone as additions for cement,” Magazine of Concrete Research, vol. 71, no. 24, pp. 1302–1311, 2019.
59. B. Y. Lee, S. M. Jeon, C. Geun Cho, and H. K. Kim, “Evaluation of time to shrinkage-induced crack initiation in OPC and slag cement matrices incorporating circulating fluidized bed combustion bottom ash,” Construction and Building Materials, vol. 257, Article ID 119507, 2020.
60. E. Benhelal, G. Zahedi, E. Shamsaei, A. Bahadori, Global strategies and potentials to curb CO_2 emissions in cement industry, J. Clean. Prod. 51 (2013) 142–161, https://doi.org/10.1016/j.jclepro.2012.10.049.
61. H.K. Yong, Y.C. Choi, Development of non-sintered zero-OPC binders using circulating fluidized bed combustion ash, Constr. Build. Mater. 178 (2018) 562–573, https://doi.org/10.1016/j.conbuildmat.2018.05.184
62. N.T. Dung, T.P. Chang, C.T. Chen, Hydration process and compressive strength of slag-CFBC fly ash materials without Portland cement, J. Mater. Civ. Eng. 27 (7) (2015), 04014213 https://doi.org/10.1061/(ASCE)MT.1943-5533.0001177.
63. A. Machowska, Z. Kledynski, I. Wilinska and B. Pacewska, “A study of the early hydration processes and properties of fly ash-slag binders,” Bulletin of Materials Science, vol. 42, no. 5, p. 213, 2019.
64. H. Hermawan, T. P. Chang, H. S. Djayaprabha, and H. A. Nguyen, “Effect of Elevated temperature on engineering properties of ternary Blended No-cement mortar,” International Conference on Civil Engineering and Materials Science, vol. 206, Article ID 02008, 2018.
65. W. Zhang, H. Choi, T. Sagawa, and Y. Hama, “Compressive strength development and durability of an environmental load-reduction material manufactured using circulating. Advances in Materials Science and Engineering fluidized bed ash and blast-furnace slag,” Construction and Building Materials, vol. 146, pp. 102–113, 2017. https://doi.org/10.1016/j.conbuildmat.2017.04.042.
66. Y.H. Wu, R. Huang, C.J. Tsai, W.T. Lin, Utilizing residues of CFB co-combustion of coal, sludge and TDF as an alkali activator in eco-binder, Constr. Build. Mater. 80 (2015) 69–75, https://doi.org/10.1016/j.conbuildmat.2015.01.062.
67. Hsu, H. M., Cheng, A., Chao, S. J., Huang, R., Cheng, T. C., & Lin, K. L. (2009). Controlled Low-Strength Materials

Containing Bottom Ash from Circulating Fluidized Bed Combustion. International Journal of Pavement Research & Technology, 2(6).
68. Sebestova, P., Ćerny, V., & Drochytka, R. (2020). Experimental study of autoclaved aerated concrete using circulating fluidized-bed combustion fly ash. Mater. Technol, 54, 157-161
69. Lee, C. J., Song, J. H., & Chung, C. W. (2021). Development of Autoclave Aerated Concrete Using Circulating Fluidized Bed Combustion Ash. Journal of the Korean Recycled Construction Resources Institute, 9(1), 58-65.
70. Xusheng, D., Zhe, X., Junjiang, L., & Lei, W. (2024). Effects of lime content on properties of autoclaved aerated concrete made from circulating fluidized bed ash. Developments in the Built Environment, 18, 100406.
71. R. Wu, S. Dai, S. Jian, J. Huang, Y. Lv, B. Li, N. Azizbek, Utilization of the circulating fluidized bed combustion ash in autoclaved aerated concrete: effect of superplasticizer, Constr. Build. Mater. 237 (2020) 117644, https://doi.org/10.1016/j.conbuildmat.2019.117644
72. Mostafa NY. Influence of air-cooled slag on physicochemical properties of autoclaved aerated concrete. Cem Concr Res 2005;35:1349–57.
73. Karakurt Cenk, Kurama Haldun, Topcu Ilker Bekir. Utilization of natural zeolite in aerated concrete production. Cem Concr Compos 2010;32:1–8
74. Y. Xia, Y. Yan, and Z. Hu, “Utilization of circulating fluidized bed fly ash in preparing non-autoclaved aerated concrete production,” Construction and Building Materials, vol. 47, pp. 1461–1467, 2013
75. X. Chen, Y. Yan, Y. Liu, and Z. Hu, “Utilization of circulating fluidized bed fly ash for the preparation of foam concrete,” Construction and Building Materials, vol. 54, pp. 137–146, 2014
76. M. Chi and R. Huang, “Effect of circulating fluidized bed combustion ash on the properties of roller compacted concrete,” Cement and Concrete Composites, vol. 45, pp. 148–156, 2014.
77. W. T. Lin, K. L. Lin, K. Chen, K. Korniejenko, M. Hebda, and M. Lach, “Circulation fluidized bed combustion fly ash as partial replacement of fine aggregates in roller compacted concrete,” Materials, vol. 12, no. 24, p. 4204, 2019.
78. J. Zhang, G. Jia, F. Yang, and P. Zhang, “Study on the affecting factors of preparation of CFBC fly ash ceramsite and its automatic design for production process,” New Building Materials, vol. 47, no. 8, pp. 134–138, 2020.
79. X. Chen, Z. Xu, Z. Yao et al., “Preparation of non-sintered lightweight aggregates through co-mechanochemical treatment of oil-contaminated drill cuttings, circulation fluidized bed combustion fly ash, and quicklime,” Environmental Science and Pollution Research, vol. 27, no. 17, pp. 20904– 20911, 2020.
80. M.A. Glinicki, D. Jóźwiak-Niedźwiedzka, M. Dąbrowski, The influence of fluidized bed combustion fly ash on the phase composition and microstructure of cement paste, Mater. 12 (2019) 2838, https://doi.org/10.3390/ma12172838.
81. B. Singh and B. Middendorf, “Geopolymers as an alternative to Portland cement: an overview,” Construction and Building Materials, vol. 237, 2020
82. Siddique, S., & Jang, J. G. (2020). Effect of CFBC ash as partial replacement of PCC ash in alkali-activated material. Construction and Building Materials, 244, 118383.
83. H. Xu, Q. Li, L. Shen, M. Zhang, J. Zhai, Low-reactive circulating fluidized bed combustion (CFBC) fly ashes as source material for geopolymer synthesis, Waste Manag. 30 (2010) 57–62, https://doi.org/10.1016/j.wasman.2009.09.014.
84. M. Eiamwijit, K. Pachana, S. Kaewpirom, U. Rattanasak, P. Chindaprasirt, Comparative study on morphology of ground sub-bituminus FBC fly ash geopolymeric material, Adv.

Powder Technol. 26 (2015) 1053–1057, https://doi.org/10.1016/j.apt. 2015.04.013
85. P. Chindaprasirt, S. Jenjirapanya, U. Rattanasak, Characterizations of FBC/PCC fly ash geopolymeric composites, Constr. Build. Mater. 66 (2014) 72–78, https://doi. org/10.1016/j.conbuildmat.2014.05.067.
86. Koukouzas, N., Ketikidis, C., Itskos, G., Spiliotis, X., Karayannis, V., & Papapolymerou, G. (2011). Synthesis of CFB-coal fly ash clay bricks and their characterisation. Waste and Biomass Valorization, 2, 87-94.