Chapter 19
Characterization and Utilization of Coal Ash for Synthesis of Building Materials

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19.1 Introduction

Coal is considered as one of the most significant sources of global energy at present, and it is being consumed widely all through the world for production of electricity. It was estimated that at present, as per the World Coal Association reports, the total share of the coal in global energy consumption is 38% (WCA 2019), a graphical representation of the global energy shares in reference with the sources is presented in Fig. 19.1. Regardless of the progress made on the renewable sources of energy in the energy sectors, the portion of coal will be 24% of the total number by 2035 (Bhatt et al. 2019).

It is reported that around 15–18.75 tons of coal is required to produce 1 megawatt of electricity, which also produces 4.3–11 tons of FA and BA (Jayaranjan et al. 2014; Asokan et al. 2005). As a result, a huge amount of coal ashes will be

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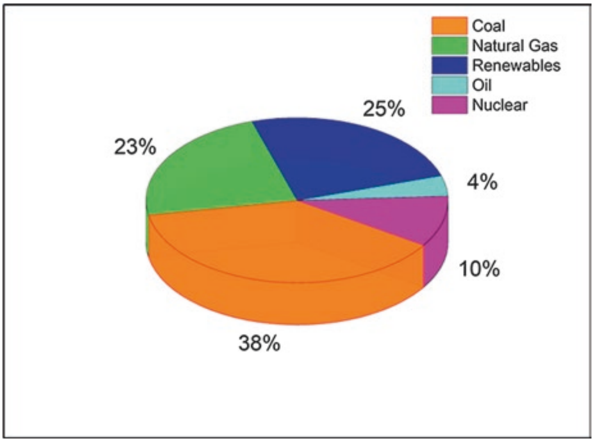

Fig. 19.1 Global energy share for the year 2019 (Data source: WCA 2019)

generated worldwide in these coming years that have the potential to contaminate both air and water (Pattanaik et al. 2019). On the contrary, construction sector is one of the major consumers of natural resources and hence it impacts the environment adversely. Therefore, several scientific investigations were made (Blissett and Rowson 2012; Queralt et al. 1997; Wang et al. 2016; Kim 2015; Jaturapitakkul and Cheerarot 2003), and also many technologies were commercialized using coal ashes as different components in building materials. Hence this chapter discusses the characteristics and utilization of coal ashes in building material synthesis. Extensive discussion has been provided on the usages of coal ash in cement composite, alkali-activated concrete, bricks/blocks, and asphalt concrete. The critical analysis has also been made on the challenges and opportunities of coal ashes in building material production to widen its practical applicability.

19.2 Coal Ash

During the combustion of coals in thermal power plants, a residual mass generates, the quantity of generation of this residue depends upon the ash content of the coal, and this residue is called coal ash (Das et al. 2019) or coal combustion residuals (CCRs). A schematic diagram has been provided in Fig. 19.2 detailing the generation of these coal ashes. The major classification of these ashes are fly ash (FA) and bottom ash (BA). This classification was done considering several parameters of the generated ash, for instance, the FA is the lighter one with very fine particles, whereas the BA is relatively heavier with large particles. The FA is extensively used in civil engineering applications, especially in cement concretes as a supplementary cementitious material (SCM) due to its good pozzolanic properties (Deschner et al. 2012). However, the BA does not possess required properties to be used as SCM in cement composites, hence most of the previous work has been conducted taking BA

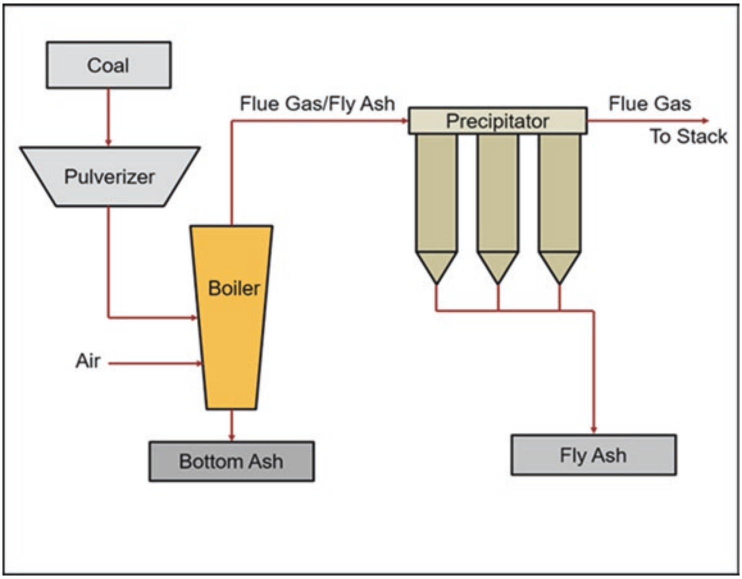

Fig. 19.2 Schematic flow chart of coal ash generation

as an alternative one to fine aggregates (Sand of river) in concrete (Singh and Siddique 2016; Andrade et al. 2009).

19.3 Physical and Chemical Properties

The physical properties of the coal ashes (both FA and BA) depend on many aspects; however, the major factors are coal grade, type and quantity of rock detritus existing inside the fissures of the coal seams, degree of pulverization before firing, the coal firing temperature, and so on. The primary distinctions in properties of both the FA and BA are discussed below taking several earlier conducted studies on the same in a more generalized approach.

19.3.1 Specific Gravity

The Specific gravity of the coal ashes depends on the chemical constitutes of the ash, mostly on the iron and calcium content. In a study, it is mentioned that if the iron content of the ash is above 10%, then the value of the specific gravity will be directly proportional to the iron percentage; however if the lime content is more than 25%, the value of the specific gravity will be more irrespective to the iron percentage (Singh and Siddique 2013). In general, the specific gravity of coal ashes lies close to 2.0; however, it can range from 1.6 to 3.1 depending upon several factors such as chemical composition (iron and calcium content), particle size, and porosity.

19.3.2 Particle Size Distribution

Particle size distribution of coal ashes plays a vital role in providing the initial rough approximations of its essential material properties such as permeability, reactivity, and specific surface area as well as its utility for different applications. For instance, a fine material with high reactivity is suitable for cement replacement, whereas a coarser material with less reactivity is more suitable for replacement of fine aggregates (natural river sand) in cement concrete. In general, the particles of FA are very fine and mostly fall under 400 μm, whereas the BA has coarser particles which could range from 1 to 2000 μm. Besides, the particle size distribution of both the ashes could vary from the abovementioned numbers depending upon several factors such as degree of pulverization of coal, firing temperature, and extent of combustion. A study conducted taking FA and BA from a thermal power plant situated at Ropar, Punjab, India (Kumar et al. 2014) where it was observed that the FA has very fine particle size gradation as compared to BA. It was found that 80% of the total FA particles are under 90 μm, whereas only 13.5% of the total BA particle fraction falls under 90 μm.

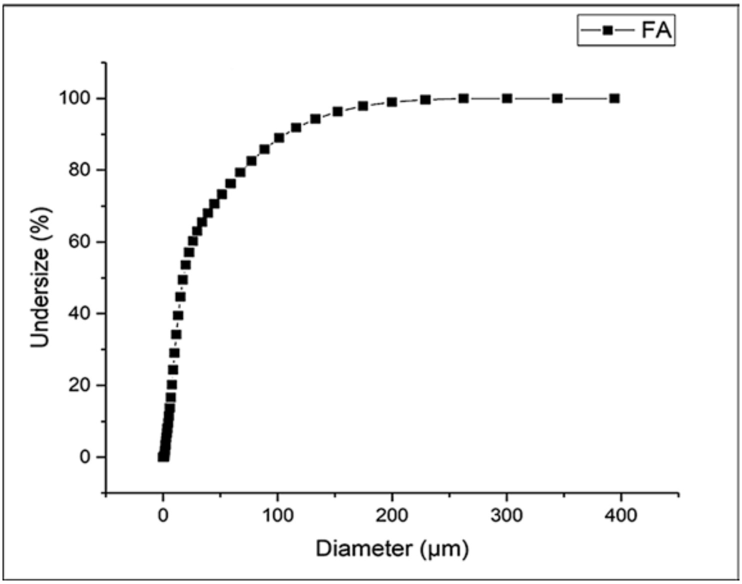

Fig. 19.3 Particle size distribution of FA from NTPC, Kaniha, Talcher, India

Figure 19.3 represents the detail distribution of particle size for FA obtained from a power plant of National Thermal Power Corporation (NTPC), Govt. of India, situated at Kaniha, Talcher, Odisha, India. The FA obtained from the NTPC had a median and mean particle size of 17.71 and 39.17 μm, respectively, whereas the d_{10}, d_{50}, and d_{90} of the same FA was 4.60, 17.71, and 106.68 μm, respectively. From the result, it can be concluded that the FA has very fine particles, whereas the BA has coarser grains in comparison.

19.3.2.1 Chemical Composition

Coal ashes are very complex to analyse, the heterogeneous composition with highly variable mineralogy provoke a major issues in concern with mineralogical characterization aspect and so as the usages of these ashes. For instance, it is found that at about 316 and 188 minerals/mineral groups was detected with coals and coal ashes, respectively (Vassilev and Vassileva 2007). However, major chemical constituents in both the FA and BA are silica (SiO_2) and alumina (Al_2O_3) with small amount of calcium content (CaO). Furthermore, as per the American Society for Testing and Materials (ASTM), the FA is classified into two-category classification based on its chemical composition (ASTM C311/C311M-18 2018), and this classification of FA is accepted worldwide. Whereas, there is no specific classification for the BA has been done, such inequality to the BA in terms of classification could be due to its limited applicability and comparatively less utility as compared to the FA. As per the ASTM classification, the FA containing 50–70% (wt.%) of $SiO_2 + Al_2O_3 + Fe_2O$ are Class C and the FA that contains more than 70% (wt.%) of the abovementioned constituents are categorized as Class F kind. Generally, the Class F type FA contains very less amount of CaO and has no self-cementitious properties, whereas the Class F type FA contains more than 10% CaO and possesses some self-cementing properties. The Class F type FA is more reactive and has higher pozzolanic characteristics, thus mostly used in cement plants as a replacement to the clinkers. The use of Class F FA is also widely seen in concrete batching plants as a suitable alternative of Portland cement (PC) during production of ready-mix concrete (RMC). The chemical composition of the coal ashes is dependent on the grade and composition of coals. For instance, the burning of lignite or sub-bituminous coals results in high calcium content coal ashes, while anthracite and bituminous coal typically result in ashes with less CaO content (Bhatt et al. 2019). The chemical assays of coal ashes reported by different authors are tabulated in Table 19.1, and it can be noticed that the major proportion of the chemical constituents are silica and alumina as discussed earlier.

Table 19.1 Chemical assay of fly ash (FA) and bottom ash (BA)

Fly ash (FA)									
	Composition								
Authors	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O	K_2O	LOI
Sutcu et al. (2019)	50.97	27.20	4.11	10.56	1.82	1.54	0.30	0.99	0.51
Van Jaarsveld et al. (2002)	61.40	33.00	1.10	0.60	0.30	2.00	0.10	0.10	0.40
Das et al. (2020b)	60.34	30.83	3.34	0.80	0.05	1.87	0.08	1.26	NA
Palomo et al. (1999b)	53.20	26.00	7.95	3.57	0.97	1.38	0.29	2.59	2.22
Fernandez-Jimenez et al. (2007)	53.09	24.80	8.01	2.44	1.94	NA	0.73	3.78	3.59
Bottom ash (BA)									
Sutcu et al. (2019)	65.02	19.18	6.86	1.76	2.00	0.93	0.85	1.93	0.05
Jang et al. (2016)	44.20	31.50	8.90	2.00	2.60	NA	NA	NA	NA
Baite et al. (2016)	62.32	27.21	3.57	0.50	0.95	2.15	0.70	2.58	NA
Kim (2015)	45.74	25.33	6.86	0.99	1.25	3.03	0.70	3.71	12.6
Cheriaf et al. (1999)	56.00	26.70	5.80	0.80	0.60	1.30	0.20	2.60	4.6

NA Not available

19.3.2.2 Pozzolanic Characteristics

The pozzolanic property of any material is referred depending on the ability of material in order to react with lime and water by forming hydrated compounds similar to C-S-H gel (Thomas 2007). In general, when the pozzolanic materials are added to the cementitious composites, they react with the free lime ($Ca(OH)_2$) obtained from hydration of cement to produce a secondary form of calcium silicate hydrate (C-S-H) gel (see Eqs. 19.1 and 19.2). This reaction is called as pozzolanic reaction, and the materials which possess such properties are called pozzolanic materials. Interestingly, the pozzolanic materials does not have self-cementitious property; they only react in the presence of lime and water. The pozzolanic reactions are comparatively slower than the hydration of cement and hence the mechanical strength developments in pozzolan blended cements are quite slow and gradual. The pozzolanic reaction can be represented as follows:

$$\text{Cement} + \text{Water} \rightarrow \text{C} \quad \text{S} \quad \text{H gel} + \text{Ca}(\text{OH})_2 + \Delta \uparrow \tag{19.1}$$

$$\text{Ca}(\text{OH})_2 + \text{Pozzolanic Material} \xrightarrow{\text{Pozzolanic reaction}} \text{C} \quad \text{S} \quad \text{H gel} \tag{19.2}$$

Pozzolanic characteristics of the coal ashes are proportional to the aluminosilicate (Si and Al) material content, amount of reactive silica, and the ratio of $Ca(OH)_2$ to pozzolana. The pozzolanic reactivity of any material is being tested by the strength activity index method as referred by ASTM standard ASTM C 311 (ASTM C311/C311M-18 2018). The strength activity index test is generally conducted for ensuring whether the adopted FA results in a satisfactory standard of strength development when blended in hydraulic cement of cement concrete. The BA shows very less pozzolanic activity due to large particle size and less reactivity. Hence the BA is mostly used as a replacement to sand in concrete and mortars. Moreover, some research works have been conducted to enhance the pozzolanic activity of the BA by applying mechanical activation method (pulverizing) (Cheriaf et al. 1999; Jaturapitakkul and Cheerarot 2003). The authors suggested that the pulverized BA can be used as a pozzolanic material in cementitious materials up to 20%; the increase in reactivity of the BA could be due to increase in specific surface area (SSA) imposed by mechanical grinding. The FA shows very good pozzolanic activity due to high reactivity, and it is being used widely in cement-based materials as an SCM.

19.3.3 Microstructural and Mineralogical Properties

The coal ashes are mostly composed of spherical particles both compact and hollow. The scanning electron microscope image of both FA and BA obtained from NTPC (Kaniha, Talcher, India) is provided in Figs. 19.4 and 19.5.

From the above figures, it can be observed that the microstructure of both the FA and BA is identical, and the same has been reported in several earlier studies (Cheriaf et al. 1999; Das et al. 2020b). It is also claimed in several occasions that the spherical shapes of these ashes help in achieving good workability performance of the blended concrete due to ball-bearing effect caused by these spherical-shaped grains (Mustakim et al. 2020). Though the FA and BA have similar microstructures in terms of morphology, but the FA founds to be significantly more reactive than BA due to its high amorphous mineralogy. A comparative microstructural investigation

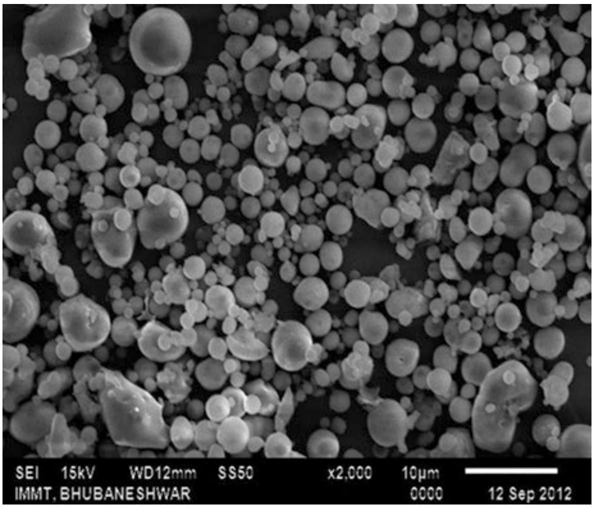

Fig. 19.4 SEM micrograph of FA from NTPC, Kaniha, Talcher, India

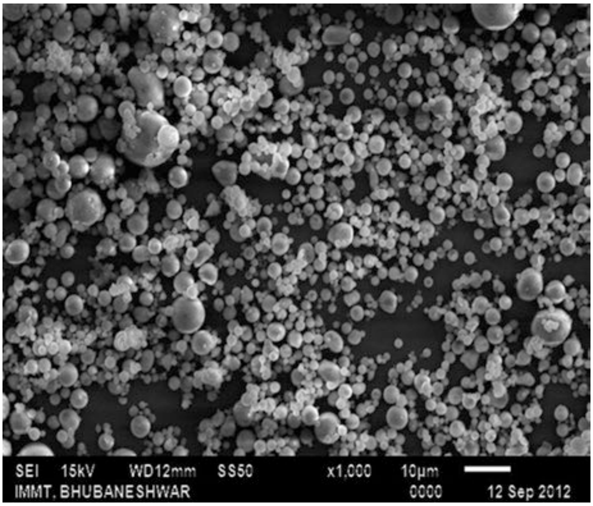

Fig. 19.5 SEM micrograph of BA from NTPC, Kaniha, Talcher, India

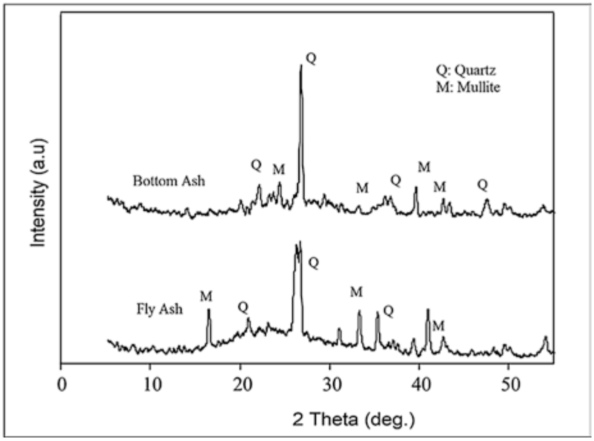

Fig. 19.6 Comparative X-ray diffractogram of FA and BA. (Adapted and reproduced from Chindaprasirt et al. 2009, with the permission)

conducted by Chindaprasirt et al. (2009) on FA and BA shows that the diffractogram (Fig.19.6) of FA is comparatively more amorphous in nature, and thus possesses higher reactivity.

From the diffractogram it can be seen that in case of FA, there exist a broad hump in between 20 and 30° (2-theta position) revealing on the amorphous nature of the material. Whereas, in case of BA, the distinct peaks of quartz and mullite are found without any broad hums which specifies less reactivity. For more detailed investigation on the reactivity of FA, a detailed diffractogram of the FA obtained from NTPC (Kaniha, Talcher) is plotted in Fig.19.7. The diffractogram of the FA shows same characteristics as obtained by Chindraprsarit et al.; however, in this case the amorphous hump located circa 15–25 ° (2-theta position).

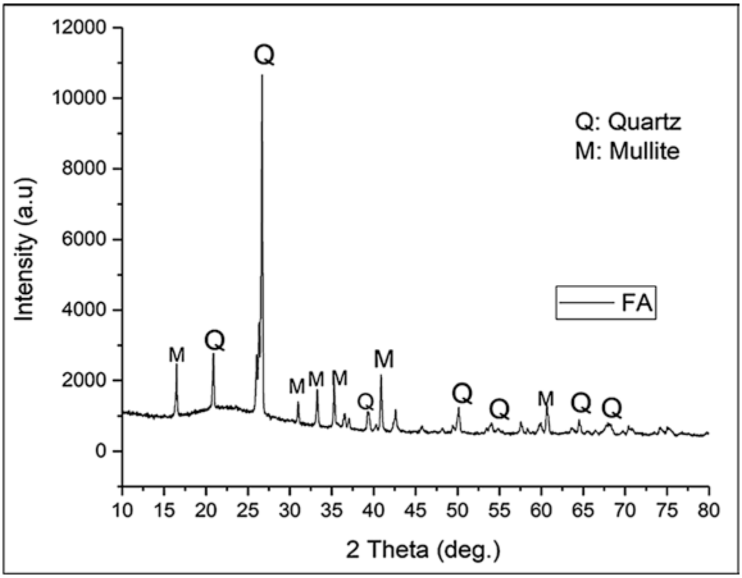

Fig. 19.7 X-ray diffractogram of FA from NTPC, Kaniha, Talcher, India

Analyzing the mineralogy, it is observed that the major components of coal ashes are quartz and mullite. Since quartz is naturally presents in the coal and hence the occurrence of this phase in coal ashes is justified, but the presence of mullite does not found in coals. Therefore, it is assumed that the formation of mullite is caused by the thermal decomposition of naturally occurring kaolinite around 980 °C. The decomposition reactions for the kaolinite in FA is described by White and Case (White and Case 1990) and the same is represented as follows.

$$Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O \xrightarrow{500^\circ C} Al_2O_3{\cdot}2SiO_2 + 2H_2O \quad (19.3)$$

$$\text{Kaolinite} \rightarrow \text{Metakaolin} + \text{Steam} \quad (19.4)$$

$$3\left(Al_2O_3{\cdot}2SiO_2\right) \xrightarrow{980^\circ C} 3Al_2O_3{\cdot}2SiO_2 + 4SiO_2 \quad (19.5)$$

$$\text{Metakaolin} \rightarrow \text{Mullite} + \text{Silica} \quad (19.6)$$

19.4 Utilization in Building Materials

19.4.1 Cement-Based Materials

Cement is one the most used material on the planet (Mishra et al. 2019), and its use is consistently raising due to the rapid urbanization and development of infrastructures. After looking close into the trend of production of cement, it can be seen that it is following a kind of geometric progression in an interval of each decade. By 1990, the global cement production was up to 1100 million tons, at present it is nearly 4370 million tons, and in 2030 the projection says it will be around 4830 million tons (Statista Research Department 2013). As the prime source of cement production is lime stone, huge amount of lime stone mining is done every year to meet the current demand. This mining activity is harshly damaging the ecosystem, and also the calcination of lime stone during cement production is causing severe environmental pollution by emitting CO_2 gas (Mishra et al. 2020). It is estimated that the carbon emission by the cement industries is around 7% of the total anthropogenic carbon discharge to the environment (Das et al. 2018). Meanwhile, both the FA and BA are considered solid waste that needs to be reused to minimize environmental pollution. These solid wastes can be reused in the cementitious materials as a replacement to cement or aggregates. These following sections summarized the utilization of FA and BA of cement and mortar as a supplement to cement/sand discussing their corresponding effect.

19.4.1.1 Fly Ash

Utilization of FA as an admixture in cement-based material has started and brought many possibilities to reuse it as a potential supplement of traditional construction of raw materials (viz. cement and sand). In 1995, Babu and Rao studied its efficiency in concrete to establish a relation between strength, water/cement ratio, age, and percentage of replacement (Ganesh Babu and Siva Nageswara Rao 1996). From their study, it was evidenced that with age the pozzolanic reaction of FA increases which increases the cementing efficiency. However, it depends on many physical and chemical characteristics like particle size, shape, and its distribution and chemical assay, glass or reactive content, respectively (Ganesh Babu and Siva Nageswara Rao 1996). In another study, Ravina (1997) used FA (Class F type) while replacing fine sand and then evaluated the properties of the fresh cement concrete. The FA mixed concrete achieved better workability as compared to the reference concrete. However, it consumed either the same or slightly higher water. It was further noticed that the FA mixed concrete required a higher setting time as compared to the reference concrete, which is caused owing to slow pozzolanic reaction. Later on, the ash handling division of NTPC Limited, India (NTPC Ash Utilization Division 2013), utilized FA as a mixer in cement for high-quality constructions, such as Delhi Metro Rail Corporation (DMRC) works and Bandra Worli Sea Link project. Different proportions of FA were used to achieve the various grades of concrete, like M30, M35, or M60, as per the desired application. Also, they reported that the FA could be used as a supplement to the Portland cement (PC) in Ready Mixed Concrete (RMC) which can be utilized in housing and infrastructure projects. In a study, Cao et al. (Cao et al. 2008) investigated the Chinese FA, which was obtained from various powerplant of China, for further recovery of minerals like alumina (Al_2O_3) from it. The alumina value present in Chinese FA is more than 40% which is needed to recover. However, the study found that it has a lot of problems to recover alumina from the FA due to the complex technology that is available, hence for the time being it was limited in lab-scale study only. Furthermore, the study concluded that FA is a good option as a construction material to utilize in cement because of its good pozzolanic reactions.

Similarly, Nochaiya et al. used FA and silica fume (SF) as a replacement in PC and examined the workability, setting time, and compressive strength of the result concrete (Nochaiya et al. 2010). The obtained compressive strength of PC-FA-SF concrete was enhanced up to 145% as compared to PC-FA concrete. However, the workability of PC-FA-SF concrete remains similar to the control concrete mixture. Higher compressive strength of the PC-FA-SF concrete was achieved because of the pozzolanic reaction and filler effect of the SF and FA in the concrete mixtures. The use of FA along with SF in PC increases the strength of concrete which shows a better option to utilize both the by-products, i.e., FA and SF. The usage of FA as a replacement of PC in cement concrete is restricted to 40% by ASTM C 595 (ASTM International 2017) while it is limited to 35% by EN 197-1 (British Standard Institution 2011). However, these limits are increased to 50–75% for lab-scale testing to maximize the use of FA. In another study, Arezoumandi et al. experimentally examined strength of reinforcing steel in cement concrete where the cement was replaced by 50% FA. The prepared beams were tested and compared to the controlled beam prepared from normal cement concrete (CC) (Arezoumandi et al. 2013). The obtained results showed that the FA beams own comparable strength to that of normal CC beams. Arezoumandi and Volz extended their work to study the effect of the increased amount of FA on the beam strength (Arezoumandi and Volz 2013). The study shows that beam having 70% Class C FA has higher shear strength compared with the 50% FA and the normal CC beams. Furthermore, they found that increase in the amount of FA in concrete increases the bond strength of reinforcing steel concrete. It occurs due to the increase in mechanical properties like flexural strength, splitting tensile strength, and fracture energy. Also, the crack pattern and failure are similar for both FA and CC beams (Arezoumandi et al. 2015). Further, Hemalatha and Ramaswamy (Hemalatha and Ramaswamy 2017) performed a review analysis on the utilization of FA to make sustainable concrete based on the fly ash characteristics. It concluded that a higher replacement of cement by FA could be possible, i.e., up to 60% by the proper scientific method to maximize the utilization.

19.4.1.2 Bottom Ash

The BA particles are coarser in size which showed less reactivity than FA. However, the BA also can be utilized as a construction material like fly ash. Cheriaf et al. has examined the pozzolanic properties of BA (Cheriaf et al. 1999). The study evaluated its strength concerning the ages of the concrete mixture. The pozzolanic reactions are accelerated gradually after 28 days and become more significant after 90 days. The compressive strength test of prepared mortar was shown that BA can be used successfully in concrete. Besides, ball milling of BA for 6 h could improve their reactivity in alkaline media resulting in enhancement of the 28-day strength by 27%. In another study the milling effect of the BA in pozzolanic activity was examined by performing grinding up to 45 microns (Jaturapitakkul and Cheerarot 2003). Both before and after grind samples were taken, and their physical and chemical properties were investigated. The study unveils that due to grinding, particle size and porosity of BA decreases which resulted in a better pozzolanic reaction. With 20–30% replacement, the compressive strength of concrete could improve after 60 days. Oruji et al. (2017) took the BA from sub-bituminous coal and ground it to improve its fineness up to three times. Then the workability, setting time, and strength of the prepared mortar were investigated. The result shows that the workability and setting time increased by 21% and 14%, respectively, with regard to control. Similarly, the compressive strength improved by 120% at the age of 90 days. The pozzolanic reactivity of BA is improved which results in better strength and improved microstructure of cement mortar due to grinding of the coarse BA. Additionally, an experimental investigation was conducted by Pyo and Kim (Pyo and Kim 2017) to develop an ultra-high performance concrete (UHPC) by utilizing BA, FA, and two different types of slag powder. From the obtained results, it is evident that both BA and FA are promising to achieve significant workability and strength.

The use of BA as replacement of sand is extensively studied as compared to the studies where it is being used as an SCM. Several authors reported the excellent performance of the BA as replacement of sand in cement-based materials (Ramadoss and Sundararajan 2014; Baite et al. 2016; Torkittikul et al. 2017; Ngohpok et al. 2018). Ramadoss and Sundararajan examined the properties of masonry mortar by replacing fine aggregates by BA with a range of 20–50% (Ramadoss and Sundararajan 2014). The study reveals that at 20% BA incorporation, both compressive strength and modulus of rupture increase after 28 days by 1.7% and 2%, respectively. Therefore, BA can be used as fine aggregates replacing natural sand in cement concrete up to 20% replacement level. Due to average fineness and resemble particle size to natural sand, BA can be a good option for the replacement of sand in concrete manufacturing process. However, it demands more water than that of the normal cement mortar. The sorptivity and coefficient of absorption of the masonry mortar improve with inclusion of BA; this could be due to the filler effect of BA that reduces the pore spaces in masonry mortar. Moreover, Kim (2015) used ground BA powder as a coarse binder to prepare mortar with good compressive strength and workability. From experimental analysis results, it was noticed that more satisfying workability of the BA-mortar mixture can be achieved over both the normal cement mortar mixture and FA-mortar mixture. Also, Baite et al. replaced sand at various volume fractions by fine aggregates of BA to obtain cementitious mortar (Baite et al. 2016). Incorporation of fine aggregates of BA in cementitious composite increases the porosity and hence water absorption rate. But, the utilization of BA reduces the specific weight due to low specific gravity as compared to the natural sand, and the thermal conductivity of the obtained composite is also reduced significantly. Thus, it promises a better option to utilize wastes, i.e., coal BA, with better performance in thermal insulation property of the building materials. It is also recommended that the BA-induced cementitious materials have better durability performance than the ordinary PC-based materials. A study was conducted by Jang et al., to perform an analysis to evaluate the deterioration in BA-mortar due to carbonation and chloride penetration (Jang et al. 2016). For a better comparison, ordinary mortar, FA-mortar, lightweight shell mortar, and slag cement mortar were included in the study. The results show that BA-mortar offered better resistance as compared to ordinary and lightweight mortar. However, FA-mortar and slag cement mortar have a better governing impact over BA-mortar while considering the chloride resistance, and the results are obvious comparing the pozzolanic reactivity of FA and slag with BA.

The thermal insulation property of the PC-based materials with BA was studied by Torkittikul et al. (2017). The study included BA as a substitute of sand at the various percentages (up to 100% replacement) and compared with the conventional mortar and concrete. The results of the conducted experiment show that the density decreases with an increase in BA% in the mortar and concrete mixture as compared to the controlled mixture; however, it does not influence the compressive strength significantly. The BA-mortar and concrete manifested enough thermal insulation properties; with an addition in BA%, the thermal conductivity reduces, which is in agreement with the earlier discussed study (Baite et al. 2016). The thermal conductivity of the BA-mortar and concrete with 100% replacement declined by 68.61% and 46.91% as compared to the control one. In another study, Ngohpok et al. have extended their study of BA in concrete (Ngohpok et al. 2018). They tested the thermal conductivity, mechanical properties, and sound absorption of pervious concrete by replacing the natural aggregates with the BA aggregates. The obtained results show that significant compressive strength can be achieved by replacing the limestone aggregates by BA aggregates. The BA-concrete achieves better thermal resistance as compared to that of natural limestone pervious concrete and hence encouraged to use.

19.4.2 Alkali-Activated Materials

The alkali activation is a chemical phenomenon that converts the glassy structures (partially/completely amorphous) of the coal ashes into a stable, compact, and strong composite with similar characteristics of cement-based materials (Palomo et al. 1999b). The use of FA in alkali-activated materials (AAMs) is widely known and accepted, whereas the use of BA in AAMs is limited. The following subsections discuss different studies conducted on AAMs taking these coal ashes and their subsequent effect on the performance of the resulting AAM.

19.4.2.1 Fly Ash

The alkali activation of FA has been extensively investigated (Al-Majidi et al. 2016; Mustakim et al. 2020; Hardjito et al. 2004; Das et al. 2020b; Assaedi et al. 2020) and implemented widely in real-time application in countries like Australia and United States. In the year 1999, Palomo et al. (Palomo et al. 1999b) extensively studied the behavior of FA in alkali activation; their study established the FA as a viable material for the synthesis of AAMs. The FA was activated using a mixture of sodium hydroxide and sodium silicate solutions, and the highest mechanical strength of the final product was in a range of 60 MPa at 85 °C (5 h). Furthermore, a research group at the Curtin University, Perth, Australia, led by Prof. Rangan, made the first effort to develop FA-based alkali-activated concrete (geopolymer concrete); they published their experimental results in the materials journal of the American Concrete Institute (ACI Materials Journal) in the year 2004 (Hardjito et al. 2004). Prior to this research, all of the earlier conducted experiments were done only on alkali-activated FA paste or mortars (Van Jaarsveld et al. 2002; Palomo et al. 1999b), hence this research made an milestone in the development of the alkali-activated FA concrete for commercial applications. Though the developed alkali-activated FA concrete performed well in both strength and durability characteristics, due to certain other limitations such as elevated temperature curing and early setting issues, its implementation at large was restricted. Henceforth, several research works have been conducted to develop alkali-activated FA binder at atmospheric temperature that does not need elevated temperature curing to gain strength (Nath and Sarker 2012; Al-Majidi et al. 2016; Das et al. 2020b). Some authors recommended the incorporation of a high-calcium precursor material into the alkali-activated FA binder system (Rangan 2014; Deb et al. 2014); this will facilitate hydration and thus will generate heat of hydration; this heat of hydration will be beneficial for the geopolymerization process of FA. Therefore, in several occasions of ambient-cured FA geopolymer/AAM development, the blast furnace slag (BFS) is used as a supplementary binder to FA (Nath and Sarker 2014; Das et al. 2020a). Since BFS also contains good amount of aluminosilicate with considerable amount of CaO (30–50%), it helps in both geopolymerization and hydration processes. It is also advised that the BFS shall be pulverized before use, which is not cost-effective and at some places where BFS is not easily available, hence making FA-BFS blend AAM in those places is not economically viable. To take care of these issues with BFS, Das et al. (2020a, b) conducted a research experiment replacing FA with lime and silica fume (SF) in very small fractions (Das et al. 2020b). Their experimental results made another milestone on the FA-based alkali-activated concrete; at 2% SF and 7.5% lime the

FA-based composition exhibited a compressive strength greater than 60 MPa in 28 days of ambient curing.

Moreover, few research works have been conducted to use FA as a primary source material for the synthesis of one-part AAM (Hajimohammadi and van Deventer 2017; Abdollahnejad et al. 2015; Ouyang et al. 2020). One-part AAM denotes a class of binder that follows the same root of alkali activation/geopolymerization, but there is no need to add liquid alkaline activator separately, instead the activator is in the solid form mixed with the solid aluminosilicate materials (FA, BFS, etc.) and therefore the process of synthesis is same as hydraulic cement concrete, i.e., "just add water." Considering the difficulty of supply chain and technological know-how of two-part AAM, one-part AAM emerged as a new sustainable alternative to both the cement-based and two-part alkali-activated concrete. Lv et al. conducted an experiment taking BFS and FA as a binder for one-part AAM (Lv et al. 2020). They have used a mixture of sodium carbonate, sodium hydroxide, and sodium silicate as alkaline activators. They claimed that their developed AAM showed great potential for practical applications since the resulted material claimed both high early and long-term strength; more than 25 MPa strength was developed within 3 days of casting and after 1 year the strength was nearly 73 MPa.

Moreover, the AAMs are more durable and less susceptible to chemical attacks. Several literatures have claimed that AAM shows excellent performance when immersed in aggressive solutions of different types such as seawater, deionized water, magnesium/sodium sulfate solution, and H_2SO_4 (Palomo et al. 1999a, b). For the better understanding of durability characteristics of any material, very profound observation is needed on its mineralogy and microstructure and essentially high mechanical strength of a material does not guarantees good durability property. Most of the durability issues of conventional cement-based materials are caused directly or indirectly by the calcium content of its binder. For instance, the sulfate attack caused by the reaction of C3A (tri-calcium aluminate) in the presence of free lime ($Ca(OH)_2$) with ingress sulfate ions from soil or water. This reaction generates ettringite and gypsum as reaction products that cause volumetric expansion leading to formation of cracks in the concrete. Another important case of durability reduction caused by lime is the reinforcement corrosion due to carbonation; in carbonation the free lime ($Ca(OH)_2$) reacts with the atmospheric CO_2 to form $CaCO_3$ precipitant. This process in cement concrete causes volumetric expansion with reduction in pH inside the matrix and hence the corrosion in reinforcements occurs. However, in case of the AAM, the reaction product that acts as the binder is an alkaline aluminosilicate gel with no free lime ($Ca(OH)_2$). Due to the unique mineralogy of AAM, it is extremely less susceptible to such chemical disintegration discussed above (Fernandez-Jimenez et al. 2007).

19.4.2.2 Bottom Ash

Though the BA does not have great reactivity like FA, still in several occasions it is being used as a precursor material for AAM. This less reactivity is generally caused by the large particle size coupled with the low specific surface area (SSA), therefore, it is suggested to pulverize the BA for enhanced reactivity before using in AAM (Osholana et al. 2020). In a study, conducted by Chindaprasirt et al. (Chindaprasirt et al. 2009), both FA- and BA-based AAM were synthesized using a mixture of NaOH and Na_2SiO_3 with three different concentrations of NaOH (5, 10, and 15 M). At a moderate level of alkali concentration (10 M), the BA-based composite exhibited a compressive strength of 18 MPa, whereas for FA the strength was 35 MPa. It is obvious that the FA will result comparatively better in mechanical properties than the BA, and the same has been reported in literature (Ul Haq et al. 2014). However, in a study it is reported that the elevated temperature curing can help achieve higher strength (Ul Haq et al. 2014); both FA and BA were taken as precursors for AAM separately, the FA-based composite resulted in 61.4 MPa, whereas the specimen made with BA shown a compressive strength of 55.2 MPa at 65 °C (48 h).

It is well known that the particle size and fineness of a material play a significant role in reactivity and the same has been reported in the case of BA in AAM. Chotetanorm et al. conducted an experiment taking different fineness of high-calcium BA (median particle sizes of 16, 25, and 32 μm) in AAM, and they have extensively investigated the mechanical properties and durability of the corresponding composites (Chotetanorm et al. 2013). Results revealed that relatively high strengths were achieved for the high-calcium BA-based geopolymer mortars. All of the specimens resulted in a compressive strength between 40.0 and 54.5 MPa. They further stated that the more fine is the BA, the better is its performance. The comparatively better performances of the fine BA were accredited to the high degree of reaction of the fine BA and the resulting less number of large pores inside the composite (0.05–100 μm) compared with those made from coarse BA. Furthermore, the BA can be used as an aggregate (fine) in AAM for the production of lightweight alkali-activated concrete (Wongsa et al. 2016) similar to the cement concrete as discussed earlier.

19.4.3 Brick and Paving Materials

19.4.3.1 Fly Ash

The ceramic industries have begun using fly ash (FA) by applying geopolymer technology for the production of ceramics materials like bricks, paver blocks, and tiles for building construction. Bricks contribute a major portion to the total consumption of building materials. Therefore, Queralt et al. used FA for making ceramic bricks (Queralt et al. 1997). The study revealed that FA could be a potential raw material for the making of bricks, tiles, and paving stone. The particle size of FA is mostly below 75 micron which reduces the milling and grinding cost of the raw material, resulting in reduction in manufacturing cost. The strength of the FA bricks is more consistent or higher over the conventional bricks. However, due to changes in the mineralogical and chemical composition of FA from region to region, no general rules can be followed for standard manufacturing.

The use of FA in brick manufacturing is widely accepted and commercialized. In general, most of the brick manufacturer practices hydraulic cement as a supplementary binder with FA and thus the manufacturing cost of the bricks substantially increases. Hence, Reddy and Gaurav carried out the study to determine the strength of lime-FA brick by adding different additives to lower the cost of production (Reddy and Gourav 2011). From the study, it was observed that the lime-pozzolana reaction rate is slow at ambient temperature and requires a long curing duration to achieve comparable strength. The 28-day strength of lime-FA brick was 10 MPa with the addition of gypsum as an additive. Maximum compressive strength can be achieved by mixing only 2% gypsum; hence it is suggested to add some gypsum with the FA-lime-based bricks for the better results. Moreover, the compressive strength can be improved by curing the bricks in a steam chamber at 80 °C; this technic helps to control the relative humidity. In another study conducted by CSIR-IMMT, Bhubaneswar, the authors have mentioned a new technology called "mineral polymerization" by which the FA can be used for building brick production without using any cement (Dwari et al. 2020). However, this new technology needs special attention for its commercialization while considering techno-economic viability.

Experimental research was carried out by Wang et al. (2016) to innovate the possible technology for the utilization of coal FA. They produced FA brick with a replacement of 50–80%; strength grade and freezing–thawing resisting were evaluated. The study unveils that high-volume FA bricks can be used as building materials. Furthermore, Fernández-Pereira et al. used biomass gasification fly ash to prepare bricks (Fernández-Pereira et al. 2011). From that study, it was obtained that the prepared FA brick has similar properties like the commercially available bricks. It can be used commercially as low-density clay masonry units having excellent thermal insulating capacity. Similarly, Zhang et al. (2012) investigated on high sulfur content FA (more than 5% SO_3 by wt.) to prepare bricks, which was collected from circulating fluidized bed combustion (CFBC). Sulfur is a harmful substance while used in building material. In this study, CFBC-FA and slag were used to prepare brick, cured in the pressurized steam chamber (Autoclave), and then the strength was tested. The brick having 77% CFBC-FA, 20% CFBC slag, and 3% of cement attained the compressive strength of up to 14.3 MPa. Due to autoclave, the bricks are of good strength and can be used commercially.

Owing to the low specific gravity of FA while comparing with cement and sand, the lightweight building blocks can be well prepared using FA. In a study, Çiçek and Çinçin examined the performance of lightweight building blocks with FA (Çiçek and Çinçin 2015). The study investigated the mechanical performance of lightweight FA blocks to replace the conventional concrete blocks. It was found that the

FA blocks developed the significant strength and less weight. Also, their thermal resistance is excellent compared to conventional concrete blocks and superior to clay bricks. The utility of FA in pavements is also suggested and experimented. Mohammadinia et al. evaluated the effect of FA in crushed brick and reclaimed asphalt pavement (Mohammadinia et al. 2017). From the strength and durability test, it was found that the unconfined compressive strength and resilient modulus were maximum for 15% FA. The addition of FA to these mixtures increases the silica and alumina crystalline and increases the binding property that ensured the well cohesion between different particles within the whole system leading to the better mechanical performances. Also, the curing temperature plays a vital role in the strength of FA-mixture samples. Higher strength could be obtained at higher curing temperatures.

Consoli et al. (2020) used CFA and carbide lime (CL) as the enhancing agents in reclaimed asphalt pavement (RAP) and evaluated its durability and performance. The results showed that the compacted RAP–FA–CL mixtures well performed under wetting–drying than freezing–thawing conditions. The porosity/lime index also plays a key role in the mechanical strength and durability. The appropriate amount of porosity/lime index can be calculated as per the requirement by geotechnical engineers. However, more investigations are needed to use FA for pavement applications for optimum design mix and performance evaluation.

19.4.3.2 Bottom Ash

The use of BA in brick is generally not preferred since there is plenty amount of FA available for brick manufacturing. Hence, most of the generated BA goes directly into ash ponds thus creates sustainability issues. A study mentioned that the total percentage consumption of FA in construction industry is 47% of total generation, whereas, for BA the number is only 5.28% (Ashish et al. 2018). Considering the future trend in the construction industries, soon in the near future there will be a shortage of FA for making building bricks. Therefore, some studies have been conducted to use BA as a constituent material for manufacturing building bricks and paving materials (Mogili et al. 2020; Sutcu et al. 2019; Ashish et al. 2018; Aydin 2016; Santos et al. 2015; Naganathan et al. 2015; Colonna et al. 2012).

An experiment conducted by Ashish et al. used BA as a replacement to sand in FA-based cement bricks (Ashish et al. 2018). Their major aim was to reduce the use of natural river sand and to use BA in bricks; nevertheless, the developed FA-BA brick performed well in comparison with the reference one. Similarly, the use of BA as replacement to sand in paving blocks is reported (Santos et al. 2015). The results indicated that the BA taken for the manufacturing of paving blocks can be used up to 50% of the natural river sand without impacting its primary properties. Further, the use of BA for paving material application was extended by Aydin (2016). He suggested a BA-cement-lime-based composite that contains 70% of BA, 25% cement, and 5% lime for manufacturing of bricks, paving blocks and floor tiles. Due to the granular particle distribution of BA, it is also recommended that the BA can be used as an aggregate to the binder in pavement binder course. Colonna et al.

(2012) studied the characteristics of the flexible binder course with incorporation of BA in place of river sand. Their results revealed when a 15% of BA was added to the mix replacing a correspondent amount of sand, the mix performed perfectly as usual like the conventional mixture, there was no deteriorating effect on the mechanical properties of the bitumen mix in comparison to the control one. It means that BA could be used for various pavement applications, however, to promote the use of this waste material (BA) for practical applications; it is essential to issue new standards for the corresponding usages of BA.

19.5 Conclusion

The discussion made in this chapter narrated the possible utilization of coal ashes (both FA and BA) in several building material applications. With the critical analysis of the results obtained in several studies by various researchers, it can be concluded that the coal ashes have promising use in synthesis of both the building and road infrastructures. Furthermore, these are good sustainable alternative of naturally available construction materials like limestone, stone dust, and sand, and hence the utilization of coal ashes can help conserve the environment as well as the corresponding natural resources.

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