
5 Fly Ash-Based Sustainable Building Materials and Life Cycle Assessment of Fly Ash

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5.1 INTRODUCTION

The pressing concerns of natural resource scarcity, fossil fuel energy usage, and total greenhouse gas emissions demand urgent action. Fossil fuels, in particular, are in great demand due to the increasing world population and the expansion of the world economy. The observed increase in consumption can be attributed directly to the concerning escalation in greenhouse gas emissions. The relationship between agricultural nitrous oxide emissions and the scarcity of natural resources by considering the interplay between agriculture, forestry, fishery value addition, fossil fuels, and total greenhouse gas emissions in the leading countries from 1971 to 2020 was investigated. Several researchers found that there exists a positive correlation between limited availability of natural resources and various industrial sectors such as agriculture, forestry, fisheries, fossil fuel energy consumption, and overall greenhouse gas emissions (Mushtaq et al. 2019; Kalombe et al. 2020; Dwivedi and Jain 2014). In the present-day scenario, the energy demands revolve around the fossil fuels, coal is one of them (Gautam et al. 2021). The major portion of coal finds usage in the thermal power plants, which in turn produces fly ash (FA). Also, there has been a significantly increased dependency on sustainability within the construction industry (Dwivedi and Jain 2014). This has raised concerns on environmental degradation, deficient energy resources, and depletion of natural resources due to increase in pollution (Tian and Sasaki 2019). As a result, the construction industry is facing the heat to incorporate more sustainable practices. Hence, it is required to find an alternative material, capable of minimizing the environmental impact and also keeping the structural integrity and functional properties intact (Yuan et al. 2023). Now, the concrete manufacturing process compromises with the environment due to its predominant cement component, which is known to release substantial amounts of carbon dioxide. The environmental impact of concrete construction might potentially be

mitigated by minimizing cement usage by the incorporation of mineral admixtures, such as FA, while maintaining durability criteria (Lu et al. 2023; Vargas and Halog 2015). Finding a solution to the issue becomes significantly more challenging when there is a corresponding rise in the quantity of FA and a decrease in the landfill capacity (Hemalatha and Ramaswamy 2021). The findings by the International Energy Agency (IEA 2021) state that due to the increased use of industrial energy at the global level, there has been a considerable amount of increase in the emission of carbon dioxide (CO_2). The expected rise in the demand of coal for 2021 was 60%, which later led to an increase of 5% in CO_2 emissions on the global level. In similar lines of study conducted, it was found that the cement industry was ranked third in terms of utilization in industrial energy and emits about 7% of CO_2 . Hence, the use of FA has become crucial in the field of civil engineering due to its significant economic and environmental implications (Radhika et al. 2022). The extent to which FA can substitute cement is constrained by the quantity of free lime present in the ash.

In the fast-developing world, coal is the largest contributor to the man-made increase of CO_2 in the atmosphere. Its environmental impact spreads far across many areas, from air pollution, water, and waste management, up to increased land uses. The face of greenhouse gas emissions, industries are seeking a new way to manage their environmental impact and reduce the carbon footprint of production. Bio-coal is also an alternative; it is carbon-neutral and aimed to replace the fossil fuels and fossil coal in industrial processes. Bio-coal is a product of bio-green pyrolysis and carbonization of raw biomass performed within controlled temperature and residence time conditions (Seow et al. 2022). Thermal conversion of biomass, which is done under the oxygen-free conditions, allows the removal of volatile organic compounds and cellulose components from the feedstock and creates a uniform, solid biofuel with characteristics similar to the ones in fossil coal. Such fuels are gaining increasing attention in the carbon-intensive industries and the launch of new bio-green production facilities dedicated to bio-coal production is heralding a new approach towards the use of fossil-free solid fuels. Bio-coal (biomass briquette) is a replacement for fossil coal, fire-wood. The demand and use of bio-coal briquettes is increasing constantly due to a number of reasons like hike in costs of other fuels and electricity; the need for energy resource security; and pollution control measures (Zhao et al. 2022).

As green building materials have been developed over the last few decades, the construction industry has adhered to very strict sustainability standards. With the increasing population, there is need for more power as well. The existence of different sources of carbon-neutral energy cannot ignore the fact that coal is inexpensive and readily available. Coal FA is a by-product which is produced by the combustion of coal, in large quantities worldwide, and this quantity continues to increase (Saraswathy et al. 2003; Hemalatha and Ramaswamy 2021). For finding sustainable alternatives for building materials, the substitution of non-renewable aggregates with recycled materials and the use of supplementary cementing materials (SCMs) such as, FA, blast furnace slag, etc., to partially or completely replace Portland cement are suggested. This substitution approach mitigates pollution in the production and manufacturing process by reducing the release of pollutants and mining waste. The researchers specifically highlighted recent developments in the characterization, compositional knowledge, hydration mechanism, activation methods, durability, and sustainability aspects of FA. The sustainable construction approach by emphasizing on the use of FA geopolymers

is emerging (Gupta, Nagpal, and Gupta 2021). The synthetization of geopolymers in the absence of aggregates, sand, or cement resulted in the reduction of the CO₂ emissions. As a result, the geopolymers produced possessed high compressive strength due to the alkali activation of FA (Xu and Shi 2018).

Various researchers have proposed potential applications of FA in several civil engineering projects, due to the advantageous physical and chemical characteristics of FA. In Figure 5.1, it can be noted that utilization of FA in the manufacturing of brick and cement contributes to 5% and 10%, respectively, with a total of 15%. In a similar manner, FA could be used as an alternative material where it can replace cement in mortar and concrete, as shown in Figure 5.1. Subsequently, the same can be done in the construction of roads, highways, as a lightweight aggregate, structural infill and for the reclamation of low-lying areas (Kalombe et al. 2020; Mushtaq et al. 2019; Rastogi and Paul 2020).

In order to cover all the major areas involving the applications of FA, a specification for pulverized FA for use as pozzolana in cement, mortar, and concrete was also released in 2003 (IS: 3812, 2003), along with four additional sections. Similarly, FA was used to update the Indian Code of Practice for plain and reinforced concrete (IS: 456, 2000). Guidelines for the application of FA in road embankments and various pavement layers have also been provided by the Indian Road Congress (IRC) (IRC: 37, 2012). As a result, the use of FA in the cement and construction industries has significantly expanded. Also, the global production share of Portland Pozzolana Cement (PPC) increased from 21.8% in 1999 to 67% in 2018. However, it might become clear that using FA only in cement and concrete would not be sufficient to use larger volumes of FA in the future; instead, new channels must be opened to boost the use of FA in other applications (Ram and Mohanty 2022; Hower et al. 2017) (Figure 5.2).

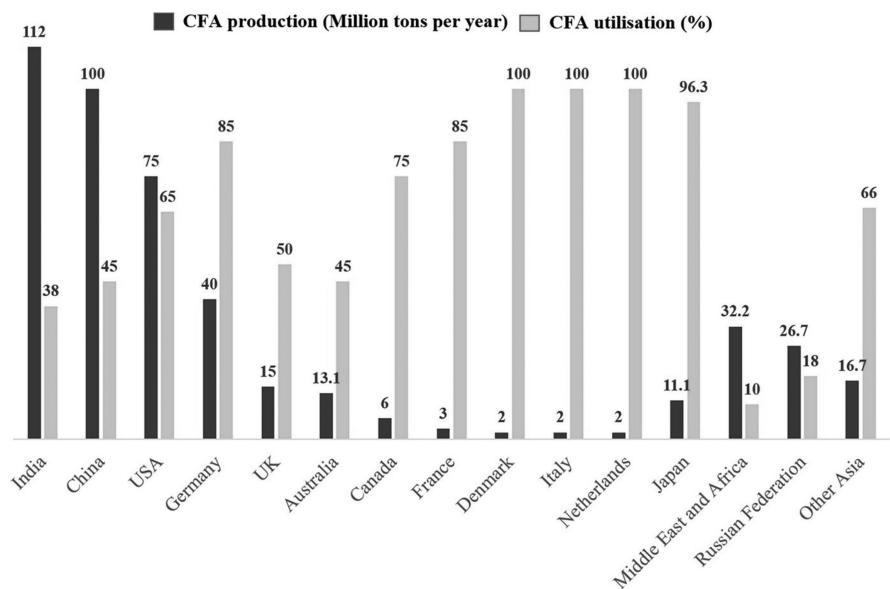


FIGURE 5.1 Production versus utilization of fly ash globally and source of origin.

5.2 FA: SOURCES, QUANTIFICATION, AND ISSUES

FA, a residual product derived from coal, has been widely employed as the predominant SCM in concrete due to its pozzolanic nature. The reaction degree of FA in cement-based materials is typically inadequate, and accurately quantifying its reaction degree is crucial for comprehending its pozzolanic hydration behaviour. Researchers identified certain components that were abundant in the unreacted FA particles but lacking in the surrounding paste. These elements were then utilized to separate the unreacted FA particles from the blended cement paste (Hower et al. 2017; Rastogi and Paul 2020). The sources of FA are illustrated in Figure 5.3 along with the percentage uses of FA shown in Figure 5.2.

5.2.1 COAL FA

It's a product of coal firing in coal power plants, at temperatures around 1,200°C–1,500°C (Yao et al. 2015). The composition of FA varies significantly depending on factors such as the type of coal, operating conditions, combustion conditions, cooling methods for flue gases, collectors, etc. This wide diversity in FA composition makes it challenging to characterize accurately.

5.2.2 MUNICIPAL SOLID WASTE FA

An increased generation of municipal solid waste (MSW) is observed, which is predominately incinerated or used in landfilling. MSW consists of organic materials and inorganic components are incinerated (Jianguo et al. 2004). It has varied compositions based on factors like location, lifestyle, education, awareness, recycling practices, etc. (Hasselriis and Licata 1996); it is a grey fine matrix with highly soluble salts, pH typically exceeding 12 (Lima et al. 2008).

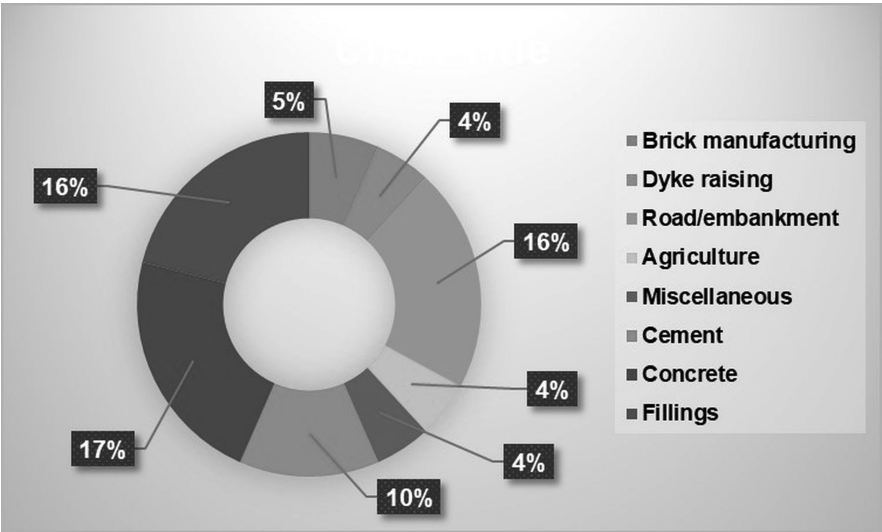


FIGURE 5.2 Percentage usage of fly ash.

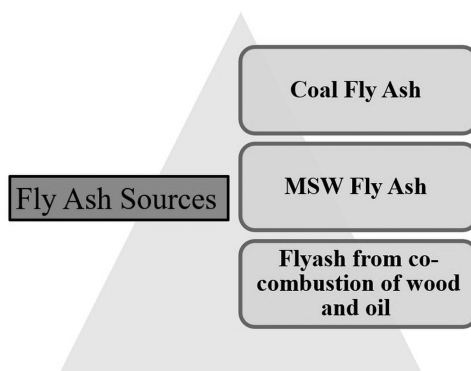


FIGURE 5.3 Sources of fly ash.

5.2.3 ASH FROM CO-COMBUSTION OF WOOD AND OIL

Combustion and co-combustion of wood and oil leads to thick grey ash. It has high pH, lesser Cl content but high iron content. It is a good source of cement production and verification processes (Lima et al. 2008).

5.2.4 INDUSTRIAL BOILERS AND BIO-COAL

Industrial boilers from various industries contribute to FA. While bio-coal is a source of carbon-neutral energy, produced by the thermal conversion of biomass anaerobically and has characteristics similar to coal, bio-coal FA is lighter than FA from other sources.

Presently, there is a need for the novel approaches to precisely measure the quantity of unreacted FA particles in blended cement systems. Researchers suggested an approach for producing the total of distinctive components considering the inherent diversity of FA. Consequently, it is possible to separate the unreacted FA particles from the blended cement system by analysing the variations in chemical composition. This would help in accurately determining the proportion of unreacted FA and the degree of reaction of FA (Rashad 2015).

In India, the production of FA has consistently increased throughout the years, specifically from 1997 to 2015. FA generation was reported to be 70 MT in 1997, and it increased to 185 MT in 2015. The utilization of FA has experienced a significant growth, rising from 8% in 1997 to 70% in 2010. In addition, 40% of the FA is yet to be utilized (Singh 2017). Many researchers consider that FA hampers the environment significantly and can be judged as a hazardous material due to the presence of potentially harmful metals in FA that include lead (Pb), arsenic (As), mercury (Hg), aluminium (Al), cadmium (Cd), chromium (Cr), vanadium (V), boron (B), and selenium (Se). The proximity of these metals to the plants growing near ash dumps resulted in variations in enzyme activity. A significant reduction in microbiological action due to the presence of FA in soil has been observed (Jambhulkar, Shaikh, and Kumar 2018).

The soil enzymatic actions undergo fluctuations and the soil respiration is negatively impacted due to the presence of FA content in the soil. The accumulation

of FA compromises with the groundwater quality in addition to that of the surface water. Further, if there are any plants in the vicinity of the FA dumping site, the soil and plants are adversely affected due to the presence of FA. The presence of coal FA basin had a negative impact on the bird population breeding in the area, leading to harmful impacts. Additionally, the offsprings of these birds led to an increase in the harmful substances such as strontium (Sr), cadmium (Cd), arsenic (As), and selenium (Se). The individuals residing in the vicinity of a thermal power plant (USEPA, 2007) experienced adverse health effects, such as cancer and respiratory diseases (Jambhulkar, Shaikh, and Kumar 2018; Chen et al. 2024).

Multiple experts have confirmed the presence of radionuclides in FA; however, the consequences are believed to be insignificant. The Bhabha Atomic Research Centre in Bombay reported that the detected radiation level in Indian coal is below the harmful limit and is very low. The presence of thorium and uranium radioactive elements was detected. However, it has been noted that their effects on the surrounding ecosystem are minimal. When FA is used for agricultural purposes, plants do not absorb any radioactive elements. The Central Fuel Research Institute in Dhanbad observed a minimal accumulation of radioactive elements by plants. FA harbours dangerous organic contaminants in addition to radionuclides. The dangerous organic pollutants include methyl sulphates, polychlorinated biphenyls, chlorinated benzofurans and dioxins, as well as polycyclic aromatic hydrocarbons.

The presence of trace elements and heavy metals in FA has the tendency to accumulate in living creatures and penetrate the food chain, resulting in hazardous consequences on both species and human health. Based on the hazardous nature of FA, especially towards the heavy metals, radionuclides, trace elements, and organic contaminants, which are of environmental importance, it can significantly affect humans, groundwater, soil, plants, birds, animals, and neighbouring water bodies. While FA is poisonous, it also contains essential minerals and trace elements that promote vegetation growth. The alkaline pH of the soil promotes plant development. Because of this characteristic, it can be utilized as both an amendment and a soil conditioner. Hence, it is essential to carry out an exploratory investigation regarding the toxicity of FA and its potential applications from an environmental standpoint (Rivera et al. 2015).

5.3 BUILDING MATERIALS

Building materials refer to substances or components used in the construction of structures such as buildings, bridges, roads, and other infrastructure. Here are some common types of building materials (Figure 5.4). Concrete is a mixture of cement, water, and aggregates (sand, gravel, or crushed stone) that solidifies into a strong and durable material. It is widely used in foundations, slabs, and structural elements. Other options are wood often used for framing, flooring, and finishing. Timber is a versatile and renewable resource. While bricks are made from clay or concrete, bricks are commonly used for constructing walls and facades.

These materials serve various purposes, including providing structural support, insulation, protection from the elements, and contributing to the overall aesthetics of the structure. Building materials can be natural or man-made and are chosen based

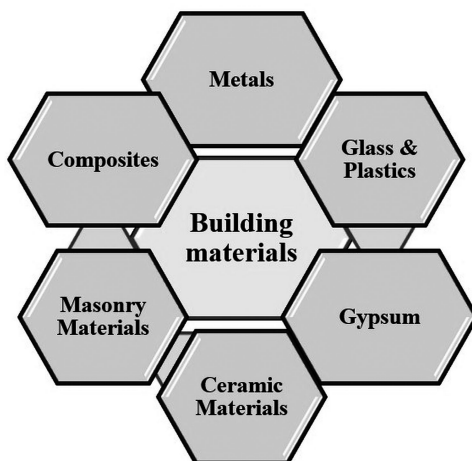


FIGURE 5.4 Different building materials.

on factors like durability, cost, availability, and the specific requirements of the construction project. Few other materials are metals like steel and aluminium that are commonly used for structural elements such as beams and columns. Copper and other metals are used for roofing and decorative purposes. Glass is used for windows, doors, and facades to allow natural light into buildings. It also contributes to the aesthetics of the structure. While plastics are used for various purposes, including pipes, insulation, and as a component in composite materials. Masonry materials are the materials besides bricks, materials like concrete blocks and natural stone are used for constructing walls. Ceramic materials are also used for tiles in flooring and walls, as well as other decorative elements. The gypsum products include drywall for interior walls and plaster for finishing.

Composite materials such as fibre-reinforced polymers (FRPs) and fibre cement, which combine different materials for improved properties.

5.4 SUSTAINABLE AND GREEN BUILDING MATERIALS

These materials are produced or taken from the environment and cause minimal impact on the environment and promote long-term ecological balance. They are often renewable, recycled, or are low in energy consumption, greenhouse gas emissions, etc. They are known for environmental friendliness, renewability, low toxicity, being durable, recyclable, and energy efficient. They offer lower carbon footprints, sustainability, and waste minimization. The key sustainable materials include bamboo, recycled materials, and eco-friendly options designed to minimize environmental impact (Kalombe et al. 2020; Yuan et al. 2023). The choice of building materials depends on various factors, including the type of construction, local climate conditions, building codes, and the specific requirements of the project. Advances in technology and “sustainable practices” continue to influence the development and use of new and innovative building materials. Apart from all the building materials listed

above, it is very important to concentrate on sustainable or green building material such as recycled aggregate, plastic and steel, sustainable concrete, green roofing materials. Sustainable and green building materials are designed to minimize environmental impact throughout their life cycle, from production and use to disposal or recycling. These materials contribute to environmentally friendly construction practices, promote energy efficiency, and reduce the overall carbon footprint of buildings. FA is a by-product of burning pulverized coal in power plants, and it is composed of fine particles that are carried away in the flue gas. Due to its pozzolanic properties, FA has been widely used as a SCM in the construction industry.

5.5 FA AS A SUITABLE SUBSTITUTE FOR BUILDING MATERIALS

FA, a residual substance produced by the combustion of pulverized coal in electric power plants, has gained growing recognition as a significant construction material owing to its potential advantages and sustainability. There are several reasons why FA can be a viable alternative to conventional construction materials (Kalombe et al. 2020; Yuan et al. 2023) (Figure 5.5).

5.5.1 UTILIZATION IN CONCRETE MAKING

FA is frequently employed as a substitute for a portion of Portland cement in the making of concrete. These improvements include increased workability, less heat generation during hydration, enhanced long-term strength and durability, and reduced environmental impact of concrete manufacturing through decreased cement usage. Concrete that includes FA is commonly known as “fly ash concrete” or “fly ash blended cement concrete” (Rastogi and Paul 2020; Hemalatha and Ramaswamy 2017).

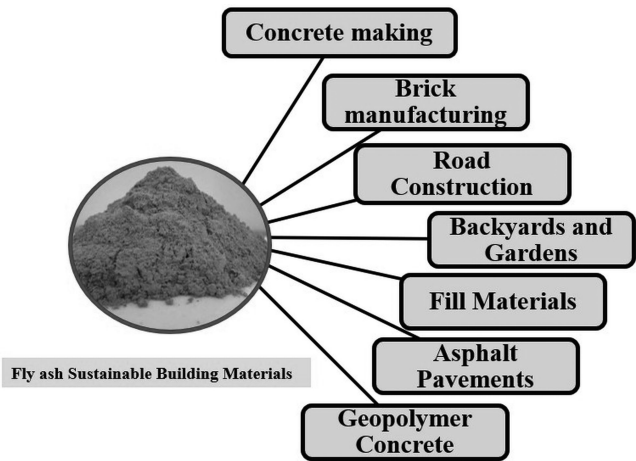


FIGURE 5.5 Fly ash-based building materials.

5.5.2 BRICK MANUFACTURING

FA can be utilized as a substitute for clay in the production of bricks. FA bricks exhibit superior compressive strength, diminished efflorescence, and decreased water absorption in comparison to conventional clay bricks. Moreover, the utilization of FA in the manufacturing of bricks diminishes the need for clay and aids in the effective disposal of FA waste (Dwivedi and Jain 2014; Rastogi and Paul 2020).

5.5.3 ROAD CONSTRUCTION

FA can serve as a stabilizing agent in road building, namely in the construction of embankments and subgrades. When FA is combined with soil, it can promote compaction, decrease permeability, boost bearing capacity, and improve the overall performance of road infrastructure.

5.5.4 FILL MATERIAL

FA can serve as a fill material in building projects, including land reclamation, back-filling of trenches, and structural fills. Due to its lightweight composition, excellent compaction qualities, and strong load-bearing capability, it may effectively replace traditional fill materials such as dirt or gravel.

5.5.5 ASPHALT PAVEMENTS

FA can be utilized in asphalt pavement construction either as a mineral filler or as a substitute for a portion of the fine aggregate. Implementing this approach can enhance the stability, longevity, and ability to withstand rutting and stripping of asphalt mixes, while simultaneously decreasing the overall expenses and environmental impact of pavement construction.

5.5.6 GEOPOLYMER CONCRETE

FA can be utilized in the manufacturing process of geopolymer concrete, which involves activating aluminosilicate minerals using an alkaline solution. Geopolymer concrete exhibits superior mechanical qualities, elevated chemical resistance, and reduced greenhouse gas emissions in comparison to conventional Portland cement-based concrete (Xu and Shi 2018; Hemalatha and Ramaswamy 2021).

In construction, the use of FA provides several benefits such as waste reduction, preservation of resources, enhanced material functionality, and decreased environmental harm. Nevertheless, it is crucial to guarantee meticulous quality control and strict compliance with pertinent norms and laws when integrating FA into construction materials (Dwivedi and Jain 2014). Lu et al. (2023) provide insights into the importance of coal fly ash (CFA) as a secondary resource, and its significant role in large-scale utilization through building material production. The authors also discussed regarding the chemical and physical properties of CFA, classification, and the present status of its utilization in various building materials like cement, geopolymers, etc. (Rivera et al. 2015).

5.6 BENEFITS OF USING FA, ITS FUTURE, AND CHALLENGES

5.6.1 BENEFITS OF USING FA

There are many benefits of using FA, it is a tool to serve for achieving a sustainable environment through utilization and waste management (Vargas and Halog 2015). The usage of FA is an important step in achieving the UN 7th, 9th, and 11th sustainable goals which emphasize affordable and clean energy; industry, innovation, and infrastructure; and sustainable cities and communities, respectively. It is noteworthy that based on the type of FA, its quality, the different applications are intended. Additionally, local regulations and standards should be considered when using FA in building materials.

The few benefits of using FA are discussed below.

a. Cement replacement in concrete

FA has been extensively used as the partial replacement for cement in concrete. It enhances workability, increased strength, and durability of the concrete. It also reduces the heat of hydration in concrete, thereby preventing thermal cracking. It gives strength and reduces water demand (Kurda, de Brito, and Silvestre 2017; Li, Wu, and Wang 2022; Kameswara Rao, Achyutha Kumar Reddy, and Venkateswara Rao 2022).

b. Improved durability

The use of FA in the concrete makes it denser and resistant to chemical attacks.

c. Economically viable

FA is a product of coal combustion in thermal power plants. It is produced in huge quantities. By using it in construction activities or for energy derivation, the cost of manufacturing or operation can be reduced (Li, Wu, and Wang 2022).

d. Environmentally sustainable approach

Being a waste product of thermal power plants, it poses a challenge of disposal. Land filling is an option, but land is also a treasure. By using it in construction activities, the greenhouse gas emissions associated with cement production can be reduced (Vargas and Halog 2015; Rivera et al. 2015).

e. FA-derived bricks and blocks offer enhanced strength and structural properties.

f. FA also contributes to soil stabilization, soil quality improvement, and land reclamation.

g. It offers an opportunity to be used in geopolymer construction reducing the carbon footprints (Ram and Mohanty 2022).

h. FA-based pavements are energy efficient, higher in strength, and stable.

5.7 FUTURE ASPECTS OF USING FA

As the future of the FA, scientific community is further aiming for practising green building projects for reduced carbon footprints. Also, it would contribute to reduction

in the greenhouse gases emissions and to save climate. In future, to save environment and surroundings, the thermal power plants may be reduced, in that case the availability of FA will be reduced. In that case, the landfilled FA, bio-coal-based FA, or synthetic FA would be in use. Furthermore, the scientific fraternity will delve into exploring the further uses of FA and would come up with more sustainable approaches to use FA. It will continue to offer sustainability, waste minimization and efficient resource utilization (Li, Wu, and Wang 2022; Vargas and Halog 2015).

5.8 CHALLENGES WITH FA

As FA is a fine powder, it behaves like a fluid when the handling rate is too high. The fluidized FA causes discharge. Even its transportation is difficult, causing air pollution.

As the world is adopting sustainable and renewable energy, thermal power-based energy will not be used in the future, therefore it leads to decrease in the availability of FA. It will affect the construction industry. Also, they lead to low mechanical strength, which also causes longer setting periods and increased permeability. In case of inadequate curing, it will affect the performance of the FA cement.

FA pollutes the air, soil, and groundwater and when disposed openly, it affects aquatic life. There are also health hazards of FA, as it contains toxic elements like lead, arsenic, mercury, cadmium, and uranium posing health risks to humans and the environment.

It is potentially toxic leading to water pollution (particularly due to mercury).

5.9 LIFE CYCLE ASSESSMENT OF FA

Life cycle assessment (LCA) is a tool for comprehensive analysis to evaluate the impacts on environment by the product throughout its lifecycle. For FA, LCA helps to evaluate and sum up the benefits and drawbacks of each stage from production to disposal. The goal of LCA of FA is to evaluate the aptness and the sustainability of FA in different applications. It also aids the user in decision-making (Ersan et al. 2022; Fernando et al. 2021; Huber, Laner, and Fellner 2018).

FA is mainly used as construction materials; therefore here we are discussing the key components of LCA of FA (Huang and Chuieh 2015; Wang et al. 2017).

1. Goal – goal is to replace the construction material in original and to be replaced by FA for the environmental sustainability and also to compare its performance.
2. Scope – it describes the depth and detail of the study. It includes system boundaries which deals with the type of study, whether it is cradle to gate (extraction to production), cradle to grave (extraction to disposal), or cradle to cradle (extraction to disposal to recycling). The scope also covers for functional units, geographical boundaries considering unit of FA or concrete, and the location of the plant or the time frame for which LCA is practised.
3. Life cycle inventory – it includes data collection for the quantification of raw material acquisition; transportation of raw material to the plant; processing of FA (energy and material required, emissions out of the plant);

transportation of FA from plant to the construction sites. Then usage in the cement is evaluated to assess the reduction in cement usage, energy, and materials required to incorporate FA into concrete or other products. Finally, the end of life of the product is evaluated where disposal or recycling of FA-based material is considered.

4. Life cycle impact assessment

It counts on the potential reduction of global warming due to emissions reduced by the replacement of cement by FA. It also deals with the reduction in the natural resource depletion by replacing the original material. FA is also a source of toxicity, therefore toxicity evaluation due to heavy metals present in FA, due to leachate on disposal, acidification potential, etc., are also assessed.

5. Interpretation

It is the end step of LCA; it comprises the significant findings either positive or negative in terms of the environment, for example, key environmental benefits such as reduced CO² emissions, conservation of natural resources, waste minimization, toxicity, etc.

5.10 CONCLUSION

FA is a by-product of thermal power plants. Its massive production is a challenge. Therefore, it finds applicability in the different industries for sustainability. Its major contribution is in the construction industry, bio-energy, conserving natural resources, and lowering greenhouse gas emissions. It is getting popular for circular economy aspects and finds its concrete role in setting the sustainable standards. Therefore, this material needs to be explored more and more to reduce the environmental pollution. The scientific fraternity is making apt use of this and in future we will have more applications. For this, LCA is must. This chapter has discussed various possible applications, challenges, and steps in LCA of this useful material.

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