A comprehensive review on coal fly ash and its application in the construction industry

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Abstract: Coal fly ash (CFA) is a coal ignition buildup at thermal power plants, which has been viewed as a hazardous waste globally. The major problems with CFA are the large volume of land needed for its disposal and poisonous heavy metal shifted to groundwater. CFA has been considered a waste and water pollutant until recently; however, CFA is a helpful material and has shown its useful value, especially in the construction industry. This review paper aims to evaluate CFA properties and validate its utilization in the construction industry to save the planet from damages associated with its disposal. The current paper surveys the potential uses of CFA as a crude material in the construction industry in catalysis, soil stabilization and replacement, brick production, cement replacement highway embankment, bricks construction, material for soil replacement and stabilization, and dams, asphalt pavement, and road construction. This review was conducted through systematic consultation of mostly recent relevant literature with a few old publications to evaluate the efficiency of CFA utilization in the construction industry. Moreover, all the literature rated CFA as a suitable material for use in the construction industry. A major drawback of CFA usage in concrete is the slow early

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PUBLIC INTEREST STATEMENT

With the rising cost of construction and building materials, especially, cement in countries like Nigeria, there is a need to devise a means of reducing the dependency on the usage of traditional materials like cement. Coal fly ash (CFA) which is a waste obtained from the coal ignition buildup at thermal power plants which has been viewed as a very dangerous waste globally. Its disposal into the environment results in polluting the land and groundwater. Therefore, CFA has been utilized as a supplementary cementitious material. Therefore, this paper surveys the probable uses of CFA as a crude material in the construction industry in catalysis, soil stabilization and replacement, brick production, cement replacements highway embankment, bricks construction, material for soil replacement and stabilization, and dams, asphalt pavement, and road construction. This will help and motivate the society in the use of CFA for building purposes which will lead to reduction in the overall cost of the building and also improve environmental sustainability.
strength development. However, this can be taken care of by accelerating the admixtures in the concrete mix. Future research tends towards production of CFA with more improved features suitable for advanced construction technology as in 3D printing construction. Conclusively, CFA is recommended for use in the construction industry based on its performance success recorded from the research findings reviewed in this paper.

Subjects: Civil, Environmental and Geotechnical Engineering; Concrete & Cement; Waste & Recycling

Keywords: coal fly ash; construction industry; waste utilization; supplementary green construction materials

1. Introduction

Coal fly ash (CFA) is the final result of the ignition of crushed bituminous/sub-bituminous coal in the radiator of nuclear energy stations. It contains mineral constituents of coal that are not consumed. CFA is generated in coal-fired electric and steam plants when coal is crushed and blown with air into the boiler burning chamber, which rapidly lights, making heat and generating a liquid mineral residue (see Figure 1). Heat is taken out from the radiator via boiler tubes to cool the line gas and cement the fluid mineral developed and afterward passed as ash. Coarse residue particles settle as base ash or slag at the foundation of the start chamber, while the lighter fine residue particles, named CFA, stay suspended in the line gas and later released as waste materials (Akinyemi et al., 2020; Gasparotto et al., 2019; León-Mejía et al., 2018; Oliveira et al., 2014; Saikia et al., 2015; Wilcox et al., 2015). CFA is a pozzolanic material with a finely isolated amorphous aluminum-silicate containing some proportions of calcium. When mixed with Portland cement and water, it will result in hydration processes that form distinctive calcium-aluminate hydrates (C-A-H) and calcium-silicate hydrates (C-S-H). The coal CFA burn-through more space in the premises of mechanical plants and are mixed in with water to deliver into CFA settling lakes or landfills. Large measures of coal CFA are taken care of as waste load or stores, whose contamination represents a threat to nature as a critical wellspring of inorganic tainting. CFA disposal is a significant issue as it adds to contamination of the soil, air, and groundwater springs.
However, the manufacturing of ordinary Portland cement, OPC, requires the consumption of huge amounts of methane coal gas just as the disintegration of limestone, bringing about noteworthy carbon dioxide emanations (Lakshmi & Vara, 2020). This production and use of cement pollute the earth, and it also diminishes significant natural resources, for example, limestone. Panda and Jena (2019) indicated that for each ton of OPC produced, nearly one ton of CO₂ is produced, depending on the method of production used. Cement manufacturing plants have been accounted for up to 1.5 billion tons of carbon dioxide released into the environment every year. (Muthadhi & Dhiyva, 2017) indicated that the overall worldwide ecological release of carbon dioxide in 2010 was assessed at 40 billion tons, with Portland cement creation representing around 7% of the all-out carbon dioxide outflows.

Consequently, replacing Portland cement with CFA could reduce cement production and thus decrease carbon dioxide emission and invariably diminish global warming because of the reduction in cement use. With increased interest and use of Portland cement in Nigeria, the concrete and cement industries need to use more green cement replacement materials such as CFA to satisfy these needs instead of increased Portland cement production. However, the utilization of CFA in the construction industry proved productive in catalysis, wood modification, cement replacement, soil stabilization, and replacement. This review endeavors to feature the administration of CFA to utilize this solid waste to spare our planet’s condition.

2. Methodology
Five electronic databases (ResearchGate, ScienceDirect, Academia.edu, Google Scholar, SciSearch, and Purdue University E-library access gave us access to numerous journals like Taylor and Francis online, Elsevier) were consulted for this study. For studies on the history of CFA utilization in the construction industry, we searched through old published literature dated as far back as 1980 (Adriano et al., 1980) and recent publications as early as 2019 (Srisradurya & Selvaprasanth, 2019). This was done to obtain the real historical origin of construction practice and capture the CFA utilization trends in the construction industry. From older days to recent times, identify research gaps and current trends, and arrive at a valid recommendation. This study focused on peer-reviewed articles, journals, Engineering Codes, and standards like BS EN 450-1 and ASTM C618. Also, data from coal combustion product production and use survey (ACAA, 2006) were used to track the global growth of CFA utilization in concrete. In our opinion, a fundamental step in gaining knowledge about the effectiveness of CFA in the construction industry is to be aware of the CFA global annual production statistics. This will better understand the big picture of the negative impact CFA disposal could cause if not utilized. Because of the variation in the quality of concrete produced by different CFA classes, we reviewed the various classes of fly and the overall physical and chemical properties of CFA.

The research strategy used in this research was recognizing sources for this literature review; several databases were utilized. At the beginning, Google Scholar was used to take the first representative of the available type of article. As for the Google Scholar, wide search words were used at the beginning to develop a list of research publications that were of basic origin and peer reviewed. Initially, we used a basic search of Assistive Technology efficiency, from the publication titles and research data obtained from Google Scholar with that finding parameters, we were able to use a better list of more refined terms when employing other sources. Through the Purdue University Library search database selector, we were also able to consult with Purdue Library research staff to assist in selecting search terms. In addition to the database search, most of the publications were located using the snowball method. The individual search nomenclature utilized was selected due to their suitability and importance in evaluating the aim of this literature review. Sources were evaluated considering many factors. First, the source has to align with the aim of the literature review based on research questions of the material. Second, the sources had to be basic source research. Any source that focused on minor source research was removed. Third, the sources had to be from a peer-reviewed journal source. In addition to these three basic factors, we also searched for types of publications that would normally include research articles that were closely aligned with our aim.
Thus, we gave much attention to publications that were focused on CFA utilization in concrete production. Finally, we ensured that most of the journals used had the most recent publication dates, and after taking this factor into consideration, we analyzed the data itself.

Close to a total of 1000 studies were reviewed. Still, only 121 (118 studies (117 publications), 2 standards (ASTM C618 and C151), and 2 codes (BS EN 450-1 and BS 197-1) were relevant to the objective of our literature which is to evaluate CFA properties and validate the effectiveness of its utilization in the construction industry. Among the publications were nine review papers, the first on the use of alkali activated fly ash ground granulated blast furnace slag to replace cement in concrete mix (Panda et al., 2021), review of the potential utilization of CFA as a raw material for use in construction industry (Dwivedi & Jain, 2014), the utilization of fly ash as a low-cost adsorbent for the removal of organic compounds and potential uses in the construction industry (Ahmaruzzaman, 2010), application of CFA in mechanical soil stabilization and amelioration for improving crop production (Jala & Goyal, 2006), review on promising application for utilization of CFA (Loya & Rowani, 2014), carbon dioxide and storage technology using CFA (Wee, 2013), and review on the incorporation of high volume CFA in concrete with reference to high-strength concrete and high-performance concrete (Aggarwal et al., 2010). Finally, the authors drew out details related to study method, research gaps, year of publication, and research outcome from the embraced studies. Finally, new development and future research in CFA technology were also highlighted from prospective findings in the construction industry.

3. Historical knowledge of coal fly ash utilization in construction

The potential for using CFA as a strengthening cementitious component in concrete has been explored since the start of the last century. Even though it was not until the mid-1900s that essential utilization of CFA in concrete began, following the groundbreaking research was carried out at the University of California, Berkeley (Papadakis & Tsimas, 2005). The past 60 years have seen CFA usage in concrete grow fundamentally. In 2005, almost 59 million tons were utilized in concrete, concrete product, and grouts globally (ACCA, 2006). Indeed, CFA has found applications in concrete at volumes going from 15% to 25% by weight of the cementitious constituent. The definite quantity used differs mainly subject to the application, the properties of the CFA, requirement parameters, and the geographic region and climatic condition (Kronbauer et al., 2013; Martinello et al., 2014; Ribeiro et al., 2013). There has been the application of additional volumes (30% to 50%) in massive constructions such as foundations and dams to control temperature rise. As of late, investigation on using high volumes (40% to 60%) in structural applications has been conducted, resulting in concrete with incredible mechanical properties and toughness (Srishadurya & Selvaprasanth, 2019). The appropriateness of CFA use as a pozzolanic component in concrete was seen as early as 1914. Notwithstanding, the annotated bibliography arranged and published by the Highway Research Board (HRB) refers to the work by Davis and his partners reported to the American Concrete Institute in 1937 as the earliest considerable investigation in the United States. Impressive pioneering and improved work in this field was directed all through the 1940s and 1950s. Although CFA utilization in concrete was not popular at that time, since just Class F was accessible around then, during this early period, the benefit of Class F CFA in concrete was established for various applications, and the benefits and disadvantages were recognized. The Bureau of Public Roads [BPR (presently FHWA)] directed examinations in the mid-1950s and presumed that a generous measure of the Portland cement in concrete could be replaced with CFA without antagonistically influencing the long-term strength of the concrete (Adriano et al., 1980). One of the BPR examines was coordinated toward assessing different test strategies for CFA and demonstrating the relationship of the characteristics of the CFA to its impact on the quality of mortar and concrete (Freeman et al., 1997).

4. Coal fly ash production across different countries

According to the investigation by Olarewaju (2016), India is the primary biggest nation for the production of CFA worldwide with the production of 112 million tons every year and use of 38%,
trailed by China having around 100 million tons with 45% use. Information from the yearly report of the National Development and Reform Commission (NDRC) of China on CFA generation and utilization shows the abundant production of CFA in China and the area of usage in Figure 2. China produces more cement and concrete with CFA generated.

Table 1 indicates that in the Netherlands, Italy, and Denmark, 100% of CFA was utilized with a yearly generation of 2 million tons and 50% to 96.3% use in the UK, Australia, Canada, France, USA, Japan, other Asia, Germany, the Middle East, and Nigeria with the yearly generation of 15, 13.1, 6, 3, 75, 96.3, 66, 85, 10, and 2 million tons, respectively. In Nigeria, under the low productivity of hydro and nuclear energy stations, coal-based power plants are the basis of Nigeria’s energy generation. However, they denote about 54% of the installed limit of utilities according to the forecasts by the Nigerian Energy Commission (Sambo, 2008). Figure 2 indicates that the USA utilizes CFA the most for all purposes except for other purposes. Europe mainly uses CFA for concrete production and rarely uses it for mining and land reclamations. However, China uses CFA mostly for cement production, concrete production, rest purposes, mining, and land reclamations. India mostly utilizes CFA for cement production, mining and land reclamations, rest purposes, and concrete production. Figure 3 shows CFA revenue speculation from 2015 to 2022. Generally, the CFA market was valued at US$ 39,548.1 Mn in 2015 and is expected to reach US$ 64,761.9 Mn by 2022, growing at a CAGR of 7.3% during the forecast period 2016–2022. Several global studies on CFA report the complex geochemistry of these residues from coal combustion (Nordin et al., 2018; Quispe et al., 2012; L. Silva et al., 2012).

5. Classes of coal fly ash
Class F, class C, and class N are the three classes of CFA as designated by ASTM C618 (ASTM C618, 2019) and BS EN 197-1 (Draft Malawi Standard (Comesa and Sadc Harmonized), 2011). The degree of silica, calcium, alumina, and iron substances differs between these classes. The synthetic properties of the CFA are by and large affected by the substance constituents of the coal
Figure 2. Global trend in utilization of coal fly ash in concrete production (Mishra et al., 2018).
consumed, which subsequently depend upon the kind of coal, which could be bituminous/sub-bituminous coal, anthracite, or lignite. Class C and Class F are the important classes of CFA.

5.1. Class F coal fly ash
Class F CFA is generated from burning bituminous or anthracite coal, usually with a low lime content (under 15%). It consists of a significant mix of alumina, silica, and iron (over 70%) compared to Class C CFA (Panda et al., 2021). Class F CFA, which contains smooth silica and alumina, needs additives or binding agents like hydrated lime, quicklime, or cement to have a cementitious property. As a replacement material, 100% CFA with an alkaline activator could replace cement. Previous research has demonstrated that class F CFA could be used as 100% cement substitution material due to its high silicate and aluminate contents (Wardhono, 2018).

Ogundiran and Kumar (2016) indicated that the development of geopolymers might be initiated by the addition of sodium silicate, an activator to a Class F CFA. Also, research by Celerier et al. (2018) proved that polymerization can also be initiated by adding an acid-like phosphoric acid and alkalis like Si and Al. Additives improve the strength and stiffness by binding the soil particles and reducing the water content. It is time-consuming and tedious to decrease the water content of high-water content soils to the ideal water content (Pandey et al., 2018). Regardless, the main challenge of using class F CFA is the requirement for high temperatures to speed up the geopolymer response to accomplish its underlying properties during the process of hardening (Lavanya et al., 2020). This may be due to the low calcium content in class F CFA.

5.2. Class C coal fly ash
Class C CFA is generated from sub-bituminous coal or lignite. Such coal yields ash with a high content of lime (from 15% to 30%), which gives it an attractive self-establishing quality. It hardens when in contact with water, resulting in increased strength over time because it contains lime. Unlike Class F CFA, Class C CFA contains over 20% lime and self-solidifies without the requirement for an activator. This property makes Class C CFA effective in geopolymerization in concrete production without cement [34]. Class C CFA has a high content of sulfate (SO₄) and alkali (Wardhono, 2018). Nigerian coal predominantly contains sub-bituminous and lignite, indicating the class of CFA obtained is Class C (Akinyemi et al., 2020; Sambo, 2008). Considering its pozzolanic properties, low cost, and accessibility, it is promising to research soil adjustment with Class C CFA. Alternatively, high Calcium content present in class C CFA produced larger quantity of Calcium-aluminate-silicate hydrate (C-A-S-H), while the higher silicon content in Class F resulted to generation of much sodium-aluminate-silicate-hydrate (N-A-S-H) produced in high silicon Class F CFA. This C-A-S-H matrix has similarity with an alkaline activator, which has comparable hydration products to that of PC concrete, however, with low Ca/Si content. This is the motivation behind why class C CFA can be made at encompassing temperature and can conquer the problem of high
temperature in the non-concrete class F CFA (Venkat et al., 2019). Different investigations have shown that Class C non-concrete mortar shows a better compressive strength compared to class F at ambient temperature due to the presence of calcium in higher quantity in class C CFA. Furthermore, high temperature impacts the strength advancement of class F non-concrete mortar, and Class F non-concrete mortar shows a better strength improvement than that of class C non-concrete mortar at high temperature (Wardhono, 2018). Table 2 shows the range of percentage oxide compound content of CFA classes contrasted with Portland cement.

### 6. Physical properties of coal fly ash

The actual properties of CFA vary extensively, relying upon the type of coal, type of heater, consumption adequacy, the content of ash in coal start strategy, and capacity game plan. CFA, by and large, has a residue topsoil surface with 65–90% of the particles having a distance across under 0.010 mm. Debris from bituminous coal is typically better contrasted with lignite (Mastura et al., 2013). CFA particles are unfilled circles (cenospheres and mesospheres; Duarte et al., 2019; L. F. O. Silva et al., 2021; Lütke et al., 2020). Generally, CFA possesses specific gravity from 1.6 to 3.1 g/cm³ and a low bulk density between 1.01 and 1.43 g/cm³ (Nowak-Michta & Kabat, 2018).

#### 6.1. Coal fly ash color

CFA can be tan to dark grey, dependent upon the measure of unburnt carbon and its mineral and chemical constituents (Korniejenko et al., 2009). CFA with high content of lime usually has light and tan colors. A brownish color is customarily associated with the iron substance. A dull, dark, to dark color is usually credited to a raised unburned carbon content. CFA color is ordinarily dependent on each power plant and the source of coal. Different ash color types are presented in Figure 4.

### Table 2. Range of sample oxide analyses of CFA classes and Portland cement (Rafiza et al., 2014)

| Compounds | Class F CFA | Class C CFA | Portland Cement |
|-----------|-------------|-------------|-----------------|
| SiO₂      | 3.2–65      | 2.0–55      | 18–30           |
| Al₂O₃     | 18–35       | 2.6–22      | 3–10            |
| Fe₂O₃     | 5–35        | 3–30        | 1–5             |
| CaO       | 0–12        | 20–85       | 45–64           |
| MgO       | 0–2         | 3–5         | 2–6             |
| SO₃       | 0–1.5       | 1.2–3       | 1–4             |
| K₂O       | 0–2         | 2–5         | 0.5–2           |
| Na₂O      | 0–2         | 2–5         | 0.2–1           |
| LOI       | 1–2         | 2–5.5       | 2–5             |

![Figure 4. Typical ash colors.](image-url)
6.2. CFA Size and shape
CFA possesses finer-particle lime or Portland cement. CFA comprises mostly spherical silt-sized particles of about 10 to 100 microns (Ogundiran & Kumar, 2016). The circular shape of CFA appears heterogenic and has different separations between particles because of the huge differences in particle diameter. These little glass circles work on the ease of concrete mix. Fineness is another significant characteristic adding to CFA pozzolanic reaction. The CFA morphology from Scanning Electron Microscope (SEM) shows that it contains amino silicate, which resembles little spherical grains, and unburnt carbon, which resembles huge irregular grains (see Figure 5). Also, morphological molecule shape information could explain the materials’ physical and mechanical properties (Singh et al., 2015).

6.3. Coal fly ash fineness
CFA can improve workability and speed up pozzolanic processes due to its fineness. The specification requires at least 66% passing the 0.044 mm (No. 325) strainer (Revathi et al., 2015).

6.4. Coal fly ash specific gravity
Though specific gravity does not influence the concrete quality, it is good to distinguish changes in other CFA properties. It could be used to measure quality control and link to various CFA attributes that may frequently be evolving (Korniejenko et al., 2009). The specific gravity of CFA ranges from 1.9 to 3 kg/m³.

6.5. Coal fly ash pH test
Research revealed that pH assessment of CFA impacts the setting season of geopolymer paste (Korniejenko et al., 2009). The pH of the CFA is usually from 4.5 to 12.0 and is mostly dependent on the particle size of the ash and subsequent concentration of trace metals contained in the CFA (Haider et al., 2016). CFA with pH appraisals goes from 8 to 11 for the most part, and encounters fast setting (Bhojantri et al., 2018). Furthermore, pH estimation of CFA is directly proportional to its CaO content. High CaO content in CFA achieves a higher pH value (Nowak-Michta & Kabat, 2018). Explicit thought should be given to the (alkaline silica) aggregate reaction when high-alkaline base CFA is used in concrete. However, there are no limitations set on the alkaline constituent of CFA by both ASTM C618 (ASTM C618, 2019) and AASHTO M 295. The ranges of physical properties of CFA as specified by ASTM C618 are presented in Table 3.
Table 3. Ranges of physical properties of CFA (Korniejenko et al., 2009)

| Property       | Value Range                      |
|----------------|----------------------------------|
| Particle size  | 1-100 µm                         |
| Bulk density   | 540–860 kg/m³ (without compaction) |
|                | 1120–1500 kg/m³ (Compacted)      |
| Specific gravity | 2.2–2.8 kg/m³                  |
| Surface area   | 300–400 m²/kg                    |

7. Compound properties of coal fly ash
The chemical properties of CFA are generally impacted by the compound substance of the coal consumed (i.e., lignite, bituminous, and anthracite). A few CFA components are amassed more in specific particles than others, and contrast in synthetic structure exists in CFA particles. In this way, the morphology of individual CFA particles considerably affects the general chemical arrangement of the CFA (Singh et al., 2015).

The chemical properties of CFA are generally estimated utilizing X-ray fluorescence spectroscopy (XRF) analysis. Several chemical analyses indicate that CFA primary constituents are like the normal earth materials (Korniejenko et al., 2009). Generally, 95–99% of the CFA comprises Si, Al, Fe, Ca, and Ti oxides, and about 0.5% to 3.5% comprises S, Mg, Mn, P, K, and Na. The remainder of the CFA is made up of minor components, for example, Fe, Ga, Hg, Ba, Br, Cd, Cl, Co, Cu, Cr, Po, As, Sb, I, In, Mo, Ni, Pb, Zn, B, Sc, Se, Sr, Ti, W, V, and Rb (Haider et al., 2016). Additionally, the CFA among these components contains harmful components. Both ASTM C618 (ASTM C618, 2019) and CSA A3001 expect CFA to go through an autoclave expansion test of ASTM C151 (ASTM C151, 2018) to show adequacy. Table 4 shows the chemical composition of CFA samples from various research, while Figure 6 shows the XRD dispersion of CFA, showing the chemical compositions of CFA particles. These findings validate that CFA is a good pozzolanic material.

8. Evaluations of the use of coal fly ash in the construction industry
Few studies have been performed on CFA application in the construction industry, particularly concrete and cement manufacturing. A few papers review has been published. Likewise, a recent review, for example, Bhajatri et al. (2018) reviewed the utilization of CFA in surface engineering, Dwivedi and Jain (2014) examined overall utilization of CFA for proper waste management, and Ahmaruzzaman (2010) presented the subtleties on characteristics of coal CFA and its specific possible applications. A review by Attarde et al. (2014) revealed that CFA finds various applications in the cement industry, construction industry, polymer industry, and pollution control. Panda et al. (2021) investigated the impact of two kinds of CFA (Class F) and (Class C) on the CBR qualities of the dark cotton soil. They found that the CBR’s impact relies upon the cohesion of the soil and the type and ratio of CFA. Adamu et al. (2018) examined roller-compacted concrete’s mechanical properties and behavior with high volume CFA, scrap elastic, and nano-silica. Olarewaju (2016) used varying degrees of CFA to explore the engineering properties of CFA concrete. Examination of soil CFA blend fortified with polyester filaments was carried out in India by Patil et al. (2020), which indicated the joined CFA effect and fiber in the soil.

Venkat et al. (2019) demonstrated that coil fibers extended the strength of CFA and changed their brittle failure into malleable ones. Tittarelli et al. (2017) discovered that the usage of CFA, as fractional substitution of one or the other concrete or total, reliably further develops the erosion opposition of aroused steel support in the crack concrete example presented wet-dry cycles in a chloride game plan. The author saw that it gives a significant synergic sway as the pozzolanic development favors the plan of a thick defensive uninvolved layer on stirred support, which stays stable even in the presence of concrete cracks. Panda and Jena (2019) tried three quantities of two-way supported CFA block sections, contrasted them, and discovered
| Oxides   | Adamu et al. (2018) and Mohammed et al. (2018) | Chen et al. (2021) | Tajunnisa et al. (2016) | Herath et al. (2021) | Wardhono (2018) | Panda et al. (2021) | Hosan and Shaikh (2021) |
|----------|-----------------------------------------------|-------------------|------------------------|----------------------|------------------|---------------------|----------------------|
| SiO₂     | 57.06                                         | 51.80             | 41.17                  | 65.90                | 30.55            | 77.10               | 51.11                |
| Al₂O₃    | 20.96                                         | 26.40             | 34.48                  | 24.00                | 18.74            | 17.71               | 25.56                |
| Fe₂O₃    | 4.15                                          | 13.20             | 11.54                  | 2.87                 | 7.48             | 1.21                | 12.48                |
| CaO      | 9.79                                          | 1.69              | 1.89                   | 1.59                 | 28.43            | 0.62                | 4.30                 |
| MgO      | 1.75                                          | 1.17              | 1.74                   | 1.18                 | 0.00             | 0.90                | 1.45                 |
| K₂O      | 1.53                                          | 0.68              | 1.05                   | 0.58                 | 0.45             | _                   | 0.70                 |
| Na₂O     | 2.23                                          | 0.31              | 0.96                   | 0.49                 | 1.5              | 0.80                | 0.77                 |
| SO₃      | _                                             | 0.21              | 0.65                   | _                    | 3.33             | 2.20                | 0.24                 |
| TiO₂     | 0.68                                          | 1.44              | _                      | 0.92                 | 1.35             | _                   | 1.32                 |
| BaO      | _                                             | _                 | _                      | _                    | _                | _                   | _                    |
| LOI      | 1.25                                          | _                 | _                      | 1.5                  | 0.57             | 0.87                | 0.57                 |
a decrease in the heaviness of the CFA block chunk when contrasted with that of control RCC. They also noted the failure example as a mix of the yield-line example of the two-way piece alongside security failure around the block units. Likewise, Mukilan et al. (2019) researched using CFA on self-compacting cement. They found that compressive strength of self-compacting concrete expanded with CFA content, a slight expansion in the split rigidity with the supported joining of CFA, and the flexural strength diminished with the expansion of CFA in self-compacting concrete. Temuujin et al. (2010) also investigated CFA-based geopolymer mortars with contrasting degrees of sand. Joseph and Mathew (2012) examined the use of antacid actuated CFA in designing properties of geopolymer concrete (GPC). This GPC gave a higher assessment of Poisons proportion, and the modulus of elasticity appeared differently than normal concrete cement. Assessment of CFA-based GPC has shown its potential in various primary applications. It has been demonstrated that CFA-based GPC has relative strength and sturdiness properties to traditional concrete cement. Crack conduct and bond strength of warmth restored GPC with supporting steel are superior to those of Portland concrete cement. CFA-based GPC primary individuals can be planned using the current plan codes and principles used for Portland concrete designs (Chang et al., 2007). Ongoing assessment has exhibited that the requirement for heat restoration of CFA-based geopolymer cement can be removed by expanding little calcium-bearing mixtures, similar to ground granulated heater slag (Lavanya et al., 2020).

This headway in room-temperature relieving of CFA-based GPC will augment its primary applications, past precast concrete individuals. CFA is used in geotechnical applications, other than the utilization in concrete development. Lakshmi and Vara (2020) analyzed the solidness properties of GPC containing CFA and metakaolin. They saw that the utilization joining of CFA in concrete decreased high water interest in concrete. The silica content of CFA builds the concrete holding and thus every one of the mechanical properties. Panda et al. (2021), surveyed the usage of salt enacted CFA and Geopolymer Blast Furnace Slag as green cement. They likewise recognize various classes of CFA. Ogundiran and Kumar (2016) found that the expansion of calcined mud to CFA geopolymer might be advantageous where early age strength acquires is significant as 25% expansion further developed the early and late ages compressive strength. They also discovered that calcined earth’s option sped up disintegration/hydrolysis of CFA and CFA was powerful in controlling the exothermic response that went with soluble disintegration. Pritam et al. (Muthadhi & Dhiyaa, 2017) additionally found that the option of CFA in geopolymer concrete works on the general strength of the substantial. It could be gathered that CFA could be effectively utilized in primary structure projects.
Nonetheless, there are issues concerning using CFA as a cement substitute in concrete. The development business and the coal-terminated force plants delivering CFA are affected via occasional components (Okunade, 2010). Their exercises are top at different occasions. The construction industry needs an enormous part of its concrete in the late spring when building conditions are ideal. At the same time, most of the debris is created all through the colder time of year. Besides, by the mid-year, coal age will be limited to twofold. Detailed work has been done worldwide on soil adjustment with coal CFA (Brooks, 2009; Neville & Brooks, 1987). Okunade (2010) tracked that the expansion of about 12.5% (by a dry load of soil) of self-establishing coal CFA gives the best adjustment when every one of the properties is seen as together for lateritic soils. Parikshith and Sekhor (2019) used CFA in soil adjustment and found CFA as a reasonable soil adjustment specialist and diminished adjustment expense. Venkat et al. (2019) investigated soil stabilization using CFA, GGBS, and coir fiber and discovered the combination to be very effective in soil stabilization. Pandey et al. (2018) researched the stabilization of soil under foundation and pavement using CFA and discovered that the addition of a specific proportion of CFA to soil is effective in tackling shrinkage, swelling, and differential settlement problems, soil properties improved on the addition of CFA up to 25%, optimum water content increased on the addition of CFA and approximately 25–35% cost reduction is achieved on using CFA replacement.

9. Applications of coal fly ash in the construction industry
The construction industry is answerable for over half of CFA. These application areas include catalysis, modified wood substitute, cement production, soil replacement, soil stabilization, bricks, structural fill/embankments, dams, asphalt pavement construction, and road construction.

CFA has overwhelmingly been utilized as a substitute for material in construction, particularly either as a raw material or as an additive in cement production. In China, around 30% and 28% of the total ash were applied in cement and concrete production in 2018, respectively. In India, around 42% and 18% of the ash delivered were used by the cement and concrete industry (Mishra et al., 2018). The information on the different approaches to utilizing CFA is fundamental for better administration of CFA and decreasing atmospheric pollution. As of late, there has been a consistent advancement in CFA usage.

9.1. Catalysis
Metal and metal oxides are broadly used as catalysts in different industrial applications. CFA essentially comprises different metal oxides with higher volumes of iron oxides. Hence, usage of CFA in heterogeneous catalysis could provide a financially savvy and environmentally friendly strategy for reusing this waste (Wang et al., 2012). Additionally, because of the higher stability of its chief part, aluminosilicates, CFA could likewise be utilized as catalyst support for different reactions. CFA-supported CaO has been utilized as a recyclable strong base catalyst. Zhang (2014) utilized nitric-acid-initiated CFA as a heterogeneous Fenton-like catalyst for p-nitrophenol evacuation from water. An evacuation pace of 98% was seen in the ideal conditions. Cho et al. (2005) studied the selective catalytic reaction (SCR) utilizing a CFA catalyst. After pretreating and loading with transition metal components, the outcomes showed that CFA could be sensibly utilized as an SCR catalyst backing to eliminate NO from vent gas. Wang et al. (2012) reported that CFA could be a successful catalyst for gas, fluid, and solid-phase reactions. For example, gas-stage oxidation of volatile organic compounds, aqueous-stage oxidation of organics, solid plastic pyrolysis, and solvent-free organic synthesis. The CFA-supported catalyst showed suitable catalytic activities in hydrocracking and hydrocarbon oxidation. Patil et al. (2020) used CFA as a composite material in reinforced aluminum using a motorized store casting technique and discovered it was suitable for structural application.

9.2. CFA use as cement replacement
The ecological benefit of utilizing alternatives depending on accessible resources, supplementary cementing materials (SCM) like CFA can be utilized as a partial replacement for Portland cement. In contrast, alternative materials can be utilized to substitute natural aggregate, delivering
a greener concrete as CFA for resource and energy consumption (Rahacek et al., 2020). This is a confirmation of the research by S. E. Kelechi et al. (2022); they observed that CFA replacement of cement by 40% reduces the CO₂ emission associated with concrete production by 35%. The way that the utilization of CFA can, by and large, enhance the durability of concrete without trading off strength has pulled in a great deal of consideration in regard to their incorporation in concrete (Papadakis & Tsimas, 2005). Dinesh et al. (2018) discovered that concrete’s compressive and split tensile strength improved when cement was partially replaced by CFA and fine aggregate was partially replaced with copper slag. Olarewaju (2016) also found that the overall engineering properties of concrete mixed with CFA were improved. Srishadurya and Selvaprasanth (2019) tried replacing a large amount of cement in the concrete mix with high volume CFA. They observed that the addition of high-volume CFA increased the compressive strength of concrete at 28 days for 40%, 50%, and 60% replacement. Also, replacement of cement with CFA in a higher volume of 40% is discovered to reduce the cost of concrete production by 14% (S. E. Kelechi et al., 2022).

9.3. Coal fly ash use as soil replacement

Numerous tests carried out indicated that the soil properties, such as bulk density, structure, and texture, were improved by the addition of CFA (Dhindso et al., 2016). Venkat et al. (2019) study the impact of CFA on engineering properties of expansive soil. Properties such as plasticity, compaction, strength, and hydraulic conductivity of expansive soil were examined, and the plasticity was diminished by about half by the addition of 20% CFA. Depending upon the type of soil, the successful CFA content for improving the engineering properties of the soil ranges between 15% and 30%. Additionally, it was demonstrated that ash can be utilized effectively as an additive for the base and sub-base layer construction of pavement, just as for the construction of embankments in compressed soils. The established procedures of soil stabilization by adding cement lime or fly ash reason huge change and improvement in strength attributes of soils. One of the most encouraging methodologies here is the utilization of CFA as a substitution to the traditional earth material will tackle the issue of provision of needed material and this will help in the sustainable development of natural resources.

9.4. Coal fly ash use in soil stabilization

CFA is an effective agent for chemical and mechanical stabilization of soils, soil drying, and control of shrink-swell (Jala & Goyal, 2006). The application of CFA in soil stabilization results in helpful development benefits like eliminating the requirement for expansive borrow materials, improving unnecessary wet or unstable subgrade, powerful cost reduction by eliminating the expansive aggregate in the pavement and decreasing the necessary pavement thickness (Pandey et al., 2018). Equally, the blend of coal CFA with lateritic soils improves the plasticity and mechanical properties of the soil, as expressed by a decrease in the liquid limit and the plasticity index. Also, concerning the impact of self-cementing CFA on density and compaction, research findings indicate that CFA builds the compacted dry density and diminishes the optimum moisture content of lateritic soils. Coal CFA stabilization builds the CBR of lateritic soils (Okunade, 2010). Usage of CFA for stabilization most importantly offers a compelling method of decreasing the burden of storage and disposal of the waste byproducts of coal combustion and the environmental and health hazards associated with them. Financially, coal CFA stabilization is a lot less expensive than stabilization with ordinary materials. CFA treatment is commonly more economical than lime.

9.5. Coal fly ash bricks

Innovation for the usage of CFA to produce building bricks has been built by the Central Fuel Research Institute, Dhanbad, India (Sharma & Akhai, 2019). Advanced applications in the use of CFA in the production of bricks for insulation purpose such as research by Korniejenko et al. (2009) with the production of flax fiber CFA composite, they build a wall with brick and elevated element prototype and monitored it for three months while subjected to relevant environmental exposure. The result not only showed environmentally friendly, sustainable, and cost-effective benefits of the
CFA composite but also discovered that the nature of fibers and its adhesion with matrix material is a key determinant to the strength properties of the bricks.

CFA can be utilized in the scope of 40–70%. Their present clay brick development surpasses 100 billion blocks every year. In such conditions and when CFA brick is technically acceptable, financially feasible and environmentally friendly, it may be suitable to focus on creating at any rate 2 billion CFA bricks every year. It would expend around 5 million tons of CFA per year, yielding gigantic net savings. CFA bricks have various benefits over the regular burnt clay bricks in that the new CFA brick innovation can dispose of carbon emission from the earth, much brick making industry which burns large quantity of coal and produces huge amounts of carbon dioxide every year. Another noteworthy advantage of the innovation is that unlike clay bricks, which utilize valuable topsoil as raw material, the new technology utilizes CFA, an undesirable residue from coal-fired power plants. This CFA is directly disposed of on large volumes of land, harming both the atmosphere and the health of the residents around power plants (Panda & Jena, 2019). The production of CFA is set to increase, while the availability of topsoil will undoubtedly diminish. A further advantage is that CFA bricks can be produced in a variety of strengths and sizes.

### 9.6. Coal fly ash application in embankments

Embankments can be built using CFA as a borrowed material to build fills and is fit to support highway structures. CFA properties are novel as an engineering material. Dissimilar to ordinary soils utilized for embankment construction, CFA has a huge uniformity coefficient comprising clay-sized particles, reduces construction cost, is very easy to handle, and has compact diminishing construction time and equipment cost. Engineering properties that will influence CFA use in embankments include grain size distribution, compaction, characteristic shear strength, compressibility, permeability, and frost susceptibility. Essentially, all CFA utilized in embankments is Class F CFA (Sharma & Akhoi, 2019). Considering the construction required for the advancement of road framework in some nations, moderate evaluations show that around 15–20 MT ash can be utilized in the development of roads and flyover embankments per annum in some regions. Generally developed by compacting earthen materials along these lines, compaction and permeability properties are imperative to the acceptable execution of the embankment. The shear strength and compressibility are likewise significant proportions of the compacted material (Pandey et al., 2018). Local soil at a backfill site might be too feeble to support.

For this reason, local soil is replaced by compacted CFA material to provide the much-needed bearing capacity and strength. The utilization of CFA in highway embankments and fills is the second most elevated utilization of this material. It on like a fine sand material, however, has a lower density (Bergado et al., 2002). Embankments and fills are additionally the most predominant use of bottom ash. Unlike the self-cementing sub-bituminous/lignite CFA, the pozzolanic bituminous CFA is mainly utilized in building structural backfills and embankments (ADAA, Cement, Concrete and Aggregates, 2009).

### 9.7. Coal fly ash in dams

Another utilization of CFA is in roller compacted concrete dams. Numerous dams in the US have been built with high CFA content. CFA reduces the hydration heat resulting in the formation of thicker placement. This has been exhibited in the Ghatghar Dam Project in India (Loya & Rawani, 2014).

### 9.8. Coal fly ash in road and pavement construction

CFA is utilized in roads construction also. Adamu et al. (2018) examined the mechanical properties and performance of roller-compacted concrete containing high-volume CFA, crumb rubber, and nano-silica. They discovered an increase in compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, and abrasion resistance of high-volume fly ash
reinforced concrete pavement upon the addition of nano-silica. Nikhil (2019) investigated the use of CFA in high volumes as a replacement for cement for concrete pavements. He discovered that CFA contains reactive constituents which react with lime and offer hydrated minerals to impact strength and nonreactive crystalline matter which give packing effect to the concrete, filling up the pores and thus increases strength. His cost analysis on different types of pavements shows that 50% replacement of CFA maximum durability and strength was achieved and proved to be economical when compared with flexible pavements and controlled concrete pavements. The optimum dosage of superplasticizer for high volume CFA concrete was 1.25% of the total cementitious materials in concrete. Mohammed & Adamu (2018) used CFA as a mineral filler in nano silica-modified Roller Compacted Rubbercrete (RCR), and they discovered that RCR performed well with a minute reduction in compressive strength on percentage replacement of fine aggregate with crumb rubber above 10%. Report of Australian Geopolymer Institute mentioned that 70,000 tons of cement-free CFA concrete with other industrial wastes like GGBS was utilized in the construction of one of the outstanding airports in Brisbane, Australia. The airport became the greenest airport in the world as at 2014 and this saved over 6,600 tons of carbon emission in the airport construction with specific flexural strength of 4.8Mpa (Glasby et al., 2015).

10. Development in coal fly ash technologies

Lately, CFA has been transformed into various sorts to better suit the different applications required. This can be an adjustment in the regular condition to upgrade better performance in use. A portion of these innovations includes carbon expulsion; ultra-fine ash, ready-mixed CFA concrete, and high-volume CFA are elaborated below.

10.1. Carbon expulsion by combustion

Elimination of carbon can easily be achieved by reusing it and generating CFA. Carbon expulsion by burning is commercially accessible (Wang et al., 2012). Carbon removal has been proven to be possible by treating high carbon CFA with supercritical water (SCW). The properties of water change from a polar liquid to a fluid with a low dielectric constant and low PH above the supercritical point (Zhang, 2014). Drzymala et al. (2005) examined carbon removal in CFA using a laboratory froth flotation machine. Harris and Wheelock (2008) extended the research to a second phase and observed that the use of a collector consisting of nonylphenol and either hexadecane or fuel oil mixed with methyl isobutanol (MIB) as a frother resulted in a reduction in the carbon content of CFA from 25.9% in one sample and 16.5% in another sample to a final level of 1% to 2%. Mei et al. (2014) investigated the efficiency of circulating fluidized bed combustor for decarbonization of CFA and discovered the method as very efficient. Sung et al. (2016) examined the recycling removal process of unburned carbon from CFA by kerosene extraction, they concluded that 15 minutes of shaking with kerosene could reduce the carbon content of unburned carbon effectively to less than 3%. Electrostatic separation essentially includes passing CFA through a high voltage electric field, hence instigating opposite charges on the CFA particles and residual carbon, while the CFA is separated afterwards (Kim et al., 2001). Electrostatic separation is commercially accessible. There are several methods of electrostatic separation, for example, Kim et al. (2001) investigated the removal of unburned carbon from coal CFA using a pneumatic tribo-electrostatic separator and they observed a clean ash of less than loss of ignition 3% was recovered. The process of carbon modification in CFA involves chemical treatment to reduce the adsorptive properties of carbon. Although carbon is not eliminated in the process, its impact on the entrainment of air is reduced (Wee, 2013).

10.2. Ultra-fine coal fly ash

Ultra-fine CFA has a mean particle diameter (MPD) of 1–5 microns compared to the normal CFA, with a maximum particle distribution (MSD) extending from 0.1 to 10 micrometers. The decreased MPD results in the speed-up of the pozzolanic reaction (He et al., 2019). In this way, the durability and strength advantages that one sees with average CFA at a late age (over
1 year) can be accomplished at a prior age (under 90 days) and with a bit of measurement of an ultra-fine CFA. Ultra-fine CFA offers more to concrete strength addition and reduction in permeability compared to regular AASHTO M 295 CFA and will perform better compared to highly reactive pozzolans (Obla, 2008). Nowadays, CFA can likewise be processed to nano sizes to hasten the reaction rate and accomplish an early strength increase in concrete. Recently, Li et al. (2011) investigated the replacement of 5% and 8% cement with ultra-fine CFA and discovered increased pozzolanic reaction, resulting in improved workability mechanical properties, hence enhanced compressive strength and reduced dry shrinkage, permeability, and chloride ion penetration which implies improved durability of the concrete mix.

Krishnaraj and Ravichandran (2021) researched the application of ultrafine CFA in masonry construction. They discovered that the ultra-fine CFA masonry block exhibited higher compressive strength, shear resistance, and more excellent bonding between the two bricks than the conventional masonry block. Feng et al. (2015) examined the properties of high-strength concrete containing ultrafine CFA. They discovered a decrease in compressive strength of concrete under temperature-matching curing conditions and an increase in resistance to permeability. Experiment results of the study by Coppola et al. (2018) on the rheological and physical performance of mortars with ultra-fine CFA concluded that there was improved compressive strength. Gao et al. (2006) optimized ultra-fine CFA fluoro gypsum high-performance highway repair materials and measured the long- and short-term mechanical properties of the concrete. They found out that both short- and long-term strength met the requirements of highway rapid repair projects. Lee et al. (2006) investigated the physical and mechanical properties along with the workability of recycled aggregate concrete containing ultra-fine CFA. They concluded that ultra-fine CFA replacement had an important effect on the performance of concrete with different amounts of recycled concrete aggregate. Li et al. (2011) also examined the properties of ultra-fine CFA high-performance road concrete and indicated a significant improvement of the permeation resistance, compressive strength, rapid freezing, and thawing.

10.3. Ready-mixed coal fly ash concrete

Ready-mixed concrete (RMC) is well known (Rahacek et al., 2020). Ditarmare et al. (2012) reported experimental results on the use of CFA RMC. They concluded that ready-mixed high-grade concrete is pumpable up to 2 hours after mixing for partial replacement of cement by 15% CFA and gives the best compressive strength and slump result, the density of concrete was not too dependent on CFA, reduced bleeding in concrete, pumping characteristics short-term and long-term durability, and surface finish was improved. Invariably, there was no significant loss in tensile and flexural strength, and the cost rate analysis showed a 22% cost reduction.

10.4. High volume coal fly ash concrete (HVCFA)

HVCFA is attributed to concrete where the CFA exceeds 30% of all the cementitious materials. One of the pioneering uses of HVCFA was in the construction of the Hungry Horse Dam in Montana (Malhotra, 2002), initiated due to several advantages like lower cost, durability, improved protection from ASR and sulfate attack, low heat of hydration, and good workability. Since the HVCFA was used in the building of dams, concrete viaducts, buildings, foundations, and retaining walls (Nikhil, 2019). Increasing the amount of CFA in concrete is not without weaknesses. At significant levels, issues might be experienced with expanded setting time resulting in low early-age strength and delay in the pace of construction. These disadvantages become especially articulated in cold weather concreting (Adamu et al., 2018, 2020).

Additionally, the durability of the concrete might be undermined for protection from deicer-salt scaling and carbonation. For some random circumstances, there will be an ideal measure of CFA that can be utilized in a concrete mix which will maximize the technical, environmental, and economic advantages of CFA use without essentially affecting the rate of construction or disabling
Table 5. Percentage dosage of CFA (Adamu et al., 2020)

| Level of CFA classification | % by mass of total cementitious material |
|-----------------------------|-----------------------------------------|
| Low                         | <15                                     |
| Moderate                    | 15-30                                   |
| High                        | 30-50                                   |
| Very High                   | >50                                     |

the long-term performance of the completed project (Ogundiran & Kumar, 2016). The optimum measure of CFA will be a component of a broad scope of parameters and must be resolved dependent upon the situation. Studies have shown that well-cured, high-volume CFA concrete with low water/cement ratio has excellent properties when mature; however, there have been few studies on the performance of concrete at a higher water/cement ratio when produced and cured under normal conditions (Adamu et al., 2018). There are numerous structures made of HVCAF concrete, for example, the Nicola Valley Institute of Technology, University of the Cariboo (Merritt, British Columbia) constructed in the year 2001 applying Eco-Smart concrete design and HVCAF containing 50% of CFA in cementitious material for foundation and slab, De Young Museum (San Francisco, CA, United States) was made with HVCAF designed with 170 kg/m³ of cement and 170 kg/m³ of class F CFA for utilization in foundations, slabs, and beams. The beams, floor slabs, and columns of the project park lane hotel/office complex, Halifax, Canada, were constructed using 55% of CFA in the total mass of cementitious material in 1988 (Srisadurya & Selvaprasanth, 2019). Also, the 25 and 30 MPa specific strength of the walls, suspended slabs, and columns of the York University computer science building in Toronto was achieved using 50% of CFA in CM. Similarly, both the footing and other structural elements of Bay View and Liu center for the study of the global issues (Vancouver, Canada) were constructed using 50% of CFA in the cement mix. Table 5 shows the dosage levels of various volumes of CFA (Malhotra & Mehta, 2005; Srisadurya & Selvaprasanth, 2019; Titarmare et al., 2012).

11. Beneficial effect coal fly ash on the properties of fresh concrete

CFA works on the usefulness of a concrete mix in light of the reduction in the water-concrete proportion of the substantial. Albeit the particular proportion of water decline shifts broadly with the idea of the CFA and various boundaries of the mix, a gross assessment is that each 10% of CFA should allow a watered decrease of essentially 3%, this infers that, at a given droop, CFA concrete streams and solidifies better compared to traditional concrete when vibrated (Sumathi et al., 2014). The use of CFA moreover works on the cohesiveness and decreases the isolation of cement. The circular molecule shape greases up the blend, simplifying it to siphon and diminishing wear on hardware. Likewise, CFA will diminish the rate and proportion of draining fundamentally because of the decreased water interest. When the draining cycle has been finished before any last completion of the uncovered chunk. Critical degrees of CFA used in concrete with low water content can essentially crash dying. The effects of CFA on the setting time lie in the properties and amount of CFA used and the concrete temperature (Kurda et al., 2017). All Class F CFA for the most part increment the setting time as do most Class C materials. Notwithstanding, some Class C materials are accounted for to decrease the setting time, and others have no effect. To effectively recognize the setting season of CFA concrete, preliminary tests should be done with genuine blend extent and materials for the work.

Moreover, concrete containing Class F CFA regularly requires a higher segment of air-entraining admixture to accomplish an agreeable air-void framework. This is, for the most part, a result of the presence of unburned carbon which ingests the admixture (Güneyisi, 2010). Hence, higher measurements of air-entraining admixture are needed as either the CFA content of the concrete increments or the carbon content of the CFA increments. Finally, the abatement in the pace of the warmth created and the inner temperature ascent of CFA
concrete has since been an inspiration for using CFA in mass concrete development (Arulrajah et al., 2016). In gigantic cement pours where the pace of warmth misfortune is pretty much nothing, the best temperature climbs in CFA concrete will be a component of the sum and creation of the Portland concrete and CFA used, alongside the temperature of the concrete at the hour of putting. Concrete with low Portland concrete substance and high CFA content (High Volume CFA) is suitable for restricting autogenous temperature rises. (Bhatt et al., 2019) in their exploration of new properties and rheology of mortar utilized without carbon and typical CFA presumed that without carbon CFA diminished the plastic thickness and expanded the efficiency of the mortar both in non-vibrated a lot of conditions, especially those with 30% substitution.

12. Beneficial effect of coal fly ash on the properties of hardened concrete
Long haul strength advancement is further developed when CFA is used, and at some age, the strength (compressive strength) of the CFA concrete will rise to that of the Portland concrete cement given that adequate treatment is given (Olamorewu, 2016). Long haul flexural and rigidity of high-volume CFA cement may be altogether better because of the proceeded pozzolanic response fortifying the connection between the glue and the total (Zabihii-Samani et al., 2018). The flexible modulus of high-volume CFA is expanded due to the presence of a tremendous measure of unreacted CFA particles which go about as fine total and on account of the low porosity of the interfacial zone. Both high volume CFA and regular high volume CFA concrete show less jerk because of the presence of the unreacted CFA and its proceeded with strength increment (Sumathi et al., 2014). It has moreover been shown that the drying shrinkage of high-volume CFA concrete is generally not precisely ordinary concrete, and this is unquestionably a direct result of the low measure of water used in delivering such concrete (Hemalatha & Ramaswamy, 2017).

13. Beneficial impact of coal fly ash on the durability performance of concrete
CFA diminishes the porosity of cement to chlorides, water, and gas. Moreover, the presence of bountiful CFA, especially those of class F, works on the obstruction of the concrete to sulfate (Tittarelli et al., 2017). Like traditional cement concrete, CFA concrete is impenetrable to cyclic freezing and defrosting the converse yet is the situation in high volume CFA concrete (Nath & Sarker, 2015). An investigation by Soha (2018) on the impact of class F CFA on the toughness properties of concrete found drying shrinkage reduction in CFA concrete due to diminished pace of hydration when contrasted with customery cement. She additionally noticed outcomes like Karaşin and Doğruyol (2014) that the CFA concrete displayed lower chloride infiltration, consumption hazard, and sulfate obstruction because of the soluble holding and low inter-connecting voids related to CFA concrete; this is similarly on account of water and gas penetrability of CFA concrete. The thickness of the cover grid was also improved due to the pozzolanic response related to the fuse of CFA in concrete. This is similar to the recent finding by S. E. Kelechi et al. (2022) on the replacement of 40% of cement in self-compacting concrete with CFA.

14. Limitations associated with coal fly ash usage in concrete
CFA concrete blend regularly achieves lower strength at early ages (Adamu et al., 2018). approaches to be braced to check water-driven addition. Formwork removal and allowing traffic flow may be postponed because of the slow gain in strength, particularly during cold periods of the year (Karaşin & Doğruyol, 2014). Diminished early strength can be overwhelmed by speeding up admixtures (Aggarwal et al., 2010). Along these lines, the fineness of CFA and the further developed usefulness of CFA concrete make it regularly harder to make (Madhavi et al., 2014). At long last, CFA is related to expanded salt scaling creation in higher amounts of CFA (Vengata, 2009). Recently, materials that enhance early strength development have been added to the mix to enhance the early strength development. In order to achieve this, research by Mohammed et al. (2018) incorporated nano-silica into the mix, while Karaşin and Doğruyol (2014) incorporated calcium carbide waste into their self-compacting concrete mix.
15. Future research
CFA undoubtedly has great potential for increased future utilization in the construction industry because of its cost-effectiveness and numerous other benefits associated with its use, especially in concrete. As human energy demand increases with technological advancements, more coal combustion will be done, and, consequently, more CFA will be generated.

Recently, there has been innovation in the design and performance of power plants to upgrade CFA processing to improve the features and quality of CFA to achieve improved properties required for future construction materials, such as NOx emission technology, nano-CFA, ultra-fine CFA, ready-mixed CFA, and high-volume CFA concrete blends.

However, the US Department of Energy is currently synergizing with researchers to develop design standards and building code for CFA construction applications. With the recent innovation of 3D printing technology in the construction industry, fiber-reinforced CFA has been proven effective for 3D construction. Kornejenko et al. (2009) examined the 28-day performance of CFA concrete and the conventional concrete containing long and short fibers as reinforcement. They observed increased flexural strength of the CFA concrete compared to the conventional concrete mix. Hence, there is a speculated potential for CFA utilization in the new 3D technology in the construction industry.

There should not be societal panic concerning the future hazard of radioactive elements in coal and CFA. There are not much radioactive elements in ample amount of the ash compared to ordinary soil (Zielinski & Finkelman, 1997). Existing literature has shown a uniform distribution of uranium throughout glassy particles. The level of uranium release is geared slowly by dissolution of CFA particles. The solubility of uranium and radium can be predicted using the P. H. Research indicated that the dissolved concentration of uranium and radium in water are not harmful (Finkelman et al., 2021). A recent study has also proven that CFA production can also be predicted 5 years ahead of time (Zahari et al., 2018). Therefore, depletion or reduction in production can be predicted early, and other alternative measures could be taken. Recent research predicts that domestic production of CFA will gradually reduce over the coming 20 years and thereafter and will stabilize next 5 years but with improved quality as a result of dry handling. Slag cement harvested CFA, ash import, natural pozzolans, low-quality ash, colloidal silica, and ground glass are proposed to replace ash if goes into extinction in the future (Larry, 2020).

16. Concluding summary
This review paper examined the various applications of CFA in the construction industry; from this literature review, the following conclusions can be drawn:

(1) CFA is suitable for utilization in the various areas of the construction industry as in modified wood substitute, cement replacement, soil replacement, soil stabilization, bricks, structural fill/embankments, dams, asphalt pavement, and road construction.

(2) CFA is suitable for use in high volumes as a cement replacement in concrete with improved strength and durability of concrete.

(3) The incorporation of CFA into construction materials results in reduced construction cost and encourages proper waste management and green sustainable environmental friendly construction.

(4) CFA utilization has been established in cementitious materials with enhanced properties. However, few limitations on the utilization of CFA in concrete do exist. Thus, the advantages of using CFA in cementitious composites overweigh its disadvantages.
Acknowledgements
The authors wish to acknowledge the Structures and Materials Research Laboratory, Prince Sultan University, Saudi Arabia, and Civil Engineering Department Bayero University Kano, Nigeria, for viable support throughout the research project.

Funding
This work was supported by the Structures and Materials Research Laboratory of Prince Sultan University, Riyadh, Saudi Arabia.

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Disclosure statement
No potential conflict of interest was reported by the author(s).

Citation information
Cite this article as: A comprehensive review on coal fly ash and its application in the construction industry, S. E. Kelechi, Musa Adamu, O. A. U. Uche, I. P. Okopkuje, Yasser E. Ibrahim & I. I. Obianyo, Cogent Engineering (2022), 9: 2114201.

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