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Detrimental Effects of Fly Ash Backfill on Retaining Wall Stability and Associated Chemical Reactions

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Abstract: Fly ash, a by-product of coal combustion in thermal power plants, has been increasingly used in civil engineering applications, including as a backfill material for retaining walls. While fly ash offers certain economic and environmental benefits, its use can pose significant risks to retaining wall stability. Fly ash, also recognized as coal fly ash, is a substantial global issue. Pollution manifests as solid waste categorized as "hazardous waste," resulting from the electricity generation process in thermal power plants. Some metals such as Al, Fe, Ca, and Magnesium constitutes over 85% of the chemical compounds and glasses found in the majority. It is consisting a chemical range from 70% to 90% including glasses of iron and alumina. silica and calcium oxide. It is important to mention that, fly ash can serve as a dependable and alternative source of ferrous materials aluminum oxide and silicon dioxide. This paper examines the detrimental effects of fly ash backfill on retaining wall stability, focusing on the geotechnical properties, potential for leaching of toxic elements, and chemical reactions that may compromise structural integrity. A comprehensive analysis of the chemical interactions between fly ash and the retaining wall materials is presented, highlighting the conditions under which these reactions are most likely to occur. The paper concludes with recommendations for mitigating the risks associated with the use of fly ash as a backfill material.

Keywords: Fly ash, Backfill material, hazardous waste

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INTRODUCTION

One million tons of fly ash is produced annually in the world, especially in the United States, China, France and India [1]. Although fly ash is not a major problem for developing countries, it poses a threat to developing countries. This is because the amount of fly ash used in some developed countries exceeds 90%. France uses almost 100% of its fly ash, indicating that fly ash is completely recycled. At the same time, in developed countries such as India, fly ash use varies between 50% and 60%, while in other developing countries this rate is less than 40% [2]. It is more serious is that millions of tons of fly ash are produced annually worldwide. Even in the 20th century, 50% of the world's fly ash was dumped near thermal power plants. Some of the major projects involving fly ash in India include the construction of Okhla Junction in Delhi using about 4,800 tonnes of fly ash; Ash was used in the development of the LPG plant of the Corporation (NTPC); Backfill is an earthen material generally used to create a strong and stable foundation. Backfill is generally made of compacted earth material [4]. A cementitious material is installed in the fire pit electrical power of the thermal generator, which is a special fly ash collected from the product after the chemical reaction of the powdered material. Depending on the demand of fly ash in different industries, its physical and chemical requirements may vary [5].

Nowadays, with the advancement of technology and research and development, fly ash has found application in ceramics and construction, adsorbents, fertilizers, landfills, geopolymers and metallurgy. Only in ceramics and construction, fly ash is used instead of cement, ceramics, paving stones, filling preparations and fillings, etc [6]. In engineering applications, there is a special need for the use of fly ash in concrete or as a recycling material. Retaining walls are an important part of civil engineering; they are designed to retain soil and prevent erosion or collapse. Fly ash is the preferred recycling material and is essential for the stability and longevity of this structure. It is a good material that is popular as a recycling material attributable to its low cost, high capacity and some useful properties such as self-hardening and reduced permeability [7]. The collapse of rock formation and soil will cause many problems: demolition of buildings, displacement of villages, and depletion of groundwater and destruction of plants. Therefore, backfilling is an important part of the safety and economy of underground industry [8]. According to the difference between waste material and geological material, various technologies such as hydraulic backfilling, stone backfilling, high water content backfilling, paste backfilling are being studied. Among them, paste packing has received more attention due to its mechanical properties, which confirm that it is suitable for use in the ground to improve ore recovery [9].

Another unique benefit of paste backfill is the reduction of the total amount of waste that can be managed on site. Fly ash backfill materials generally consist of cement clinker, waste material, water and aggregates. Although fly ash paste backfill technology has some environmental and economic benefits, the cost and transportation of paste backfill are still a problem. Therefore, the paste backfill process should be evaluated according to the location of the coal mine and the nearby waste. There is no universal solution for backfilling or disposal of waste machinery. Environmental impact. In addition, rainwater falling on fly ash containing heavy metals can cause heavy metals to mix into soil, groundwater and eventually into large areas of water resources. This will cause pollution in water due to the increase in heavy metals and pose a threat to aquatic life and animals. Coal, which is abundant in minerals, is the source of fly ash. [10].

The main components are silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) present in it. It also contains negligible amount of 'oxides' such as K_2O, CaO, Na_2O and phosphorus 'oxides', as well as numerous oxides of transition metals. Fly ash also contains many toxic substances such as lead, nickel, cobalt, chromium, cadmium, zinc, molybdenum, arsenic, mercury, etc., which are classified as "hazardous substances" and pose a threat to flora. Air pollution produced by fly ash may be bad, but there is a high composition of useful substances in fly ash, which is good. Since fly ash is obtained from coal, coal contains large amounts of silica, alumina and iron, which are elements usually found in burning ash [11].

FLY ASH COMPOSITION

Fly-ash that are found in elements found in geological systems, such as mineral, trace element and compounds. Morphologically, fly ash is spherical, size is ranging from 200 nm to 10 µ. Structurally, it has steel balls, senospheres, aluminosilicate spheres or multilayer spheresand irregularly shaped carbon particles [12]. Because of its hollow structure, 'cenospheres havea low density,' and 'cenospheres' are currently used as fillers in cement to produce low-density concrete. The quantity of unburned carbon in 'fly ash' determines its 'colour', which can range from 'yellowish brown' to 'gray to black' [13]. The 'fly ash's carbon concentration decreases with its lighter color. The bulk density and porosity of fly ash are crucial factors that affect the ‘embankment's; ‘strength’, ‘compressibility’ and ‘drainage capabilities’. The fly ash's carbon concentration decreases with its lighter color. Fly ash typically has a ‘specific gravity of 2.1-3.0’ and a specific surface area that ranges from 170 m^2/kg to 1000 m^2/kg. As seen in Figure 1, fly ash is divided into two classes, Class F and Class C, in accordance with ‘ASTM C618’ (‘American Society for Testing and Materials standard’).

The main modification of both is determined by the proportion of iron, calcium, silicon, and alumina, respectively. The proportion of chemicals contained in fly ash is determined by the nature of the ‘coal burned’, i.e. ‘anthracite’ and ‘bituminous coal’. When old hard anthracite coal is burned, class F fly ash is formed, which was ‘pozzolanic’ in ‘nature’ due to the presence of 10% lime (CaO). This type of coal is used as ‘class F fly ash’ using ‘silica’ and ‘alumina’ with addition of ‘binders’ such as ‘portland cement’, slaked lime or quicklime. In addition to chemical activators such as ‘sodium silicate’, ‘Class F fly’, ash contributes to the formation of geopolymers. In class C, the combustion of ‘young sub-bituminous coal’ to produce fly ash contains ‘pozzolanic’ and ‘self-cementing properties’. Over time, water is added to make it harder and increase its strength. ‘Class C fly ash’ consumes additional ‘20% lime’ and high proportions of ‘alkali’ and ‘sulphate $(SO)_4$’ [13].

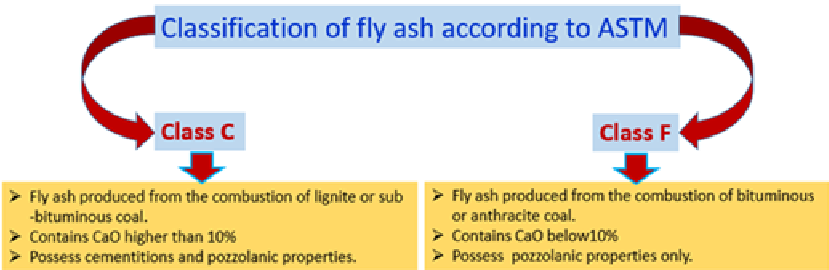


Figure 1: Fly ash classification according to American society for testing and material (ASTM) illustrating the main differences.

Fly ash is divided into primary, secondary and tertiary phase according to the time of formation. The basic phase does not change when coal is burned secondary phases including oxides and silicates are formed, In addition, fly ash such as portland stone and gypsum is transferred to create tertiary phases. The ‘cooling rate of fly ash’ particles affects the formation of inorganic substance. Rapid cooling forms small glass substances, ‘while slow cooling forms large crystalline particles’. Inorganic substances composed of amorphous and crystalline phases are the important features of fly ash. The CaO content increase, the amounts of SiO_2, Al_2O_3 and Fe_2O_3 decrease. However, as the CaO content increase, the amount of alkalis including ‘Na_2O’, ‘K_2O’ as well as ‘SO_3’ also increase.

The ‘density of fly ash’ was analysis by the iron and carbon contents. Therefore, as the C content of fly ash increase the density decrease and as the Fe content increase, the density of fly ash increase. The amount of carbon in fly ash affects its workability and water requirement. The difference in carbon content between fly ash grades is determined by calculating ‘the loss on ignition (LOI)’ [14]. Table 1 shows the typical series of component is present in Indian fly ash.

Table 1. Series of component is present Indian fly ash formed from changed coal types (‘expressed as percent by weight’)

S.N.	Component	Bituminous	Sub-bituminous	Lignite
1	SiO_2	20-60	40-60	15-45
2	Al_2O_3	5-35	20-30	10-25
3	Fe_2O_3	10-40	4-10	4-15
4	CaO	1-12	5-30	15-40
5	MgO	0-5	1-6	3-10
6	SO_3	0-4	0-2	0-10
7	Na_2O	0-4	0-2	0-6
8	K_2O	0-3	0-4	0-4
9	LOI	0-15	0-3	0-5

For building embankments and structural backfills, bituminous (pozzolanic) fly ash is more commonly utilized than sub-bituminous or lignite (‘self –cementing’) fly ash. The latter type's self-cementing properties, which harden practically instantly when water is added, are partly to blame for this.

GEOTECHNICAL PROPERTIES OF FLY ASH

There are many soil characteristics that affecting the usage of fly ash as a backfill material. These factors including particle size, specific gravity, moisture content, sealing properties, shear strength and permeability, directly affect the performance of fly ash in wall applications [15].

- **Grain Size Distribution and Compaction**:

Particle size distribution is important in providing a first estimate of the engineering material such as permeability, strength and swelling and its suitability for use construction purpose and other industries. Fly ash generally has a fingrained structure, which affects its compaction behavior. It generally requires more moisture than normal soil to produce good light. This high water content causes increased ‘pore water pressure’ that reduce the effectives stress and ‘shear strength’ in recovered material.

- **Moisture Sensitivity and Shear Strength**:

Fly ash is sensitive to changes in moisture content, which can change shear strength. When wet, the strength and stiffness usingbackfill decreases, increasing the potential instability of the retaining wall. The results for maximum depth and moisture content varying based on their classification is used as backfilling materials. The results will also be different for the same plant at different times.

- **Drainage**: Although fly ash is impermeable when compacted, changes in particle size distribution and the presence of unburned carbon will cause inhomogeneities that affect the flow. Poor drainage can cause water to collect behind the retaining wall, increasing the hydrostatic force and reducing the stability of the retaining wall.
- **Permeability/hydraulic conductivity**:

In case the reuse of ‘fly ash in concrete’, the permeability of concrete and reactivity of fly as are important.

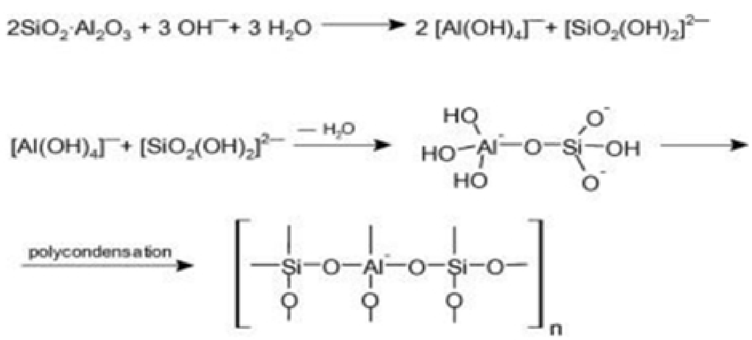
Less permeable solution to increase durability of concrete. ‘Permeability of fly ash’ can impact the quality if we can have using ‘soil stabilization’.

Hydraulic conductivity is measured by measuring dead load or head loss.

CHEMICAL REACTIONS OF ‘FLY ASH WITH RETAINING WALL’ MATERIALS

It is included a variety of chemical components, including silica, alumina, iron oxides, and unburnt carbon, as well as trace elements like arsenic, lead, and mercury. When used as backfill, these components can undergo chemical reactions with the retaining wall materials, potentially compromising structural integrity [16-17].

- **Alkaline Reactions**: Fly ash is often alkaline due to the presence of calcium oxide and other basic oxides. When fly ash comes into contact with water, these oxides can react to form calcium hydroxide, increasing the pH of the backfill environment. This high pH environment can be detrimental to concrete retaining walls, leading to alkali-silica reactions (ASR). ASR can cause expansion and cracking of the concrete, thereby reducing the structural integrity for ‘retaining wall’.



- **Sulfate Attack**: Some fly ashes contain significant amounts of sulfates. When these sulfates come into contact with water, they can form sulfate ions, which may react with the calcium aluminate phases in concrete to form expansive ettringite. This sulfate attack can lead to cracking, spalling, and eventual deterioration of concrete retaining walls.

$$Ca(OH)_2 + Na_2SO_4 + 2H_2O \xrightarrow{Yields} CaSO_4.2H_2O + NaOH$$

In other way, Sulfates combine with calcium hydroxide generated during cement hydration to form calcium sulfate (gypsum). The concrete fracture due to internal pressure and expansion caused by gypsum’s larger volume than the sum of its constituent parts. Aluminate compounds from Portland cement react chemically with sulfates and calcium to form a compound called ettringite (calcium sulphoaluminate). Ettringite formation destroys the material in the same way for gypsum formation.

$$Na_2SO_4 + H_2O \xrightarrow{Yields} 2Na^+ + SO_4^{2-}$$

- **Leaching of Toxic Elements**: Fly ash may leach toxic components example ‘arsenic’, ‘lead’, and 'mercury', particularly the acidic conditions. The leaching of these elements can not only pose environmental hazards but also weaken the bond between the retaining wall materials and the backfill. Additionally, the leachates can alter the chemical environment around steel reinforcements in reinforced concrete walls, potentially accelerating corrosion.

$$Al_2O_3 + 3H_2O + 2OH^- \rightarrow 2[Al(OH)_4]^-$$

$$SiO_2 + H_2O + OH^- \rightarrow [SiO(OH)_3]^-$$

$$SiO_2 + 2OH^- \rightarrow [SiO_2(OH)_2]^{2-}$$

- **Pozzolanic Reaction:** Fly ash contains amorphous silica (SiO_2) and alumina (Al_2O_3), which form with 'calcium hydroxide' ($Ca(OH)_2$) in the occurrence in water to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). This reaction is beneficial in stabilizing fly ash, but improper hydration or environmental conditions may reduce its effectiveness.

While pozzolanic reactions help in immobilizing harmful elements within the fly ash, incomplete or partial reactions in the environment can result in free $Ca(OH)_2$, which increases the alkalinity of surrounding soil or water.

- **Carbonation**: Fly ash is prone to carbonation when exposed to atmospheric CO_2. The $Ca(OH)_2$ in fly ash reacts with carbon dioxide to form calcium carbonate ($CaCO_3$), which may cause a reduction in alkalinity.

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow \text{C-S-H}$$

$$Al_2O_3 + Ca(OH)_2 + H_2O \rightarrow \text{C-A-H}$$

Carbonation decreases the pH of fly ash, lowering its buffering capacity. This could influence the mobility of heavy metals, potentially making them more bioavailable and 'higher risk' of groundwater contamination.

- **Sulfate Attack:** Sulfates present in fly ash (e.g., calcium sulfate, magnesium sulfate) can react with calcium-bearing compounds, especially in a moist environment. This reaction forms expansive compounds such as ettringite and gypsum, which lead to volumetric expansion and cracking.

$$CaSO_4 + \text{C-A-H} + H_2O \rightarrow \text{Ettringite}\ (Ca_6[Al(OH)_6]_2(SO_4)_3 \cdot 26H_2O)$$

Sulfate attack can lead to physical disintegration of fly ash-based structures or backfills, causing instability in retaining walls and ground structures. In addition, gypsum formation can lead to waterlogging in soils.

- **Percolating of 'Heavy Metals'**: Fly ash contains trace amounts of 'toxic heavy metals', including arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg), bound in various mineral forms. Particularly in acidic or extremely alkaline environments, these metals have the ability to seep into soli or groundwater.

Under acidic conditions, metal ions are solubilized:

$$PbO + 2H^+ \rightarrow Pb^{2+} + H_2O$$

Similarly, arsenic can leach out in both acidic and alkaline conditions due to its amphoteric nature:

$$As_2O_3 + 6H^+ \rightarrow 2As^{3+} + 3H_2O$$

The filtering of 'heavy metals' can lead to groundwater and soil contamination, posing environmental and health risks to surrounding ecosystems and human populations.

- **Interaction with Organic Compounds:** Fly ash can adsorb organic pollutants due to its high surface area and porosity. However, in moist environments, organic acids (e.g., humic and fulvic acids) from soil or decaying organic matter may interact with fly ash, altering its surface chemistry and potentially releasing bound heavy metals.

  Organic acids can complex with metal ions, leading to metal mobility:

$$Pb^{2+} + \text{Organic Acid} \rightarrow \text{Pb-Complex}$$

These interactions can mobilize toxic metals, 'higher risk' of environmental contamination.

- **Acid-Base Reactions**: Fly ash often contains free lime (CaO), which reacts with water to form $Ca(OH)_2$, prominent to high alkalinity. Fly ash reacts is with $Ca(OH)_2$ and other basic oxides when it is exposed to acidic conditions, neutralizing the alkalinity and causing the dissolution of mineral components.

$$CaSO_4 + 2H_2O \rightarrow \text{Gypsum}$$

This neutralization reaction can effect is liberation of 'heavy metals' and other toxic components from the fly ash. Acid rain or acidic groundwater may accelerate these reactions, leading to increased environmental pollution.

- **Formation of 'Secondary Minerals'**: Over time, 'secondary minerals' can form in fly ash as a result of environmental exposure, especially in humid or wet conditions. For example, minerals like gypsum ($CaSO_4 \cdot 2H_2O$), ettringite, or zeolites (aluminosilicate minerals) can form due to chemical reactions with atmospheric or groundwater constituents.

$$CaSO_4 + 2H_2O \rightarrow \text{Gypsum}$$

These secondary minerals may either stabilize the fly ash or lead to swelling, cracking, and disintegration, which could affect the structural stability of materials if we will be using fly ash.

- **Hydration and Dissolution**: According to the moisture contain, certain constituents of 'fly ash', like free lime and calcium silicates, undergo hydration, leading to the formation of stable compounds (e.g., C-S-H). However, some fly ash constituents, such as unreacted glassy phases, may dissolve slowly in water, releasing ions into the environment.

$$CaO + H_2O \rightarrow Ca(OH)_2$$

$$SiO_2 + H_2O \rightarrow \text{Dissolution of Silica Ions}$$

The release of ions can alter their 'chemical composition' of nearby soil and water, contributing to alkalinity or silica-rich deposits in surrounding environments.

- **Potential Reactions**:

Fly ash, rich in iron oxides or other transition metals, could potentially catalyze redox reactions involving organic pollutants through Fenton-like reactions (Fe^{2+}/Fe^{3+} cycling) under environmental conditions.

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + OH^- + OH\bullet$$

Similarly, fly ash could facilitate **photocatalytic degradation** of certain organic compounds, especially under UV exposure, based on the presence of metal oxides such as titanium dioxide (TiO_2).

- **Reaction Atmospheric Pollutants on Fly Ash**: The interaction between fly ash and **atmospheric pollutants** (e.g., SO_2, NO_x, or volatile organic compounds) under ambient conditions has not been extensively studied. While fly ash is known to interact with moisture and CO_2 (carbonation), the potential for reactions with gaseous pollutants could lead to unexpected chemical transformations.

Fly ash could react with sulfur dioxide (SO_2), the development of sulfate minerals (e.g., gypsum), especially under high humidity conditions.

$$SO_2 + CaO + H_2O \rightarrow CaSO_4 \cdot 2H_2O(\text{Gypsum})$$

Fly ash could also adsorb NO_x compounds, leading to secondary reactions that alter its surface properties or trigger nitrosation reactions, possibly forming harmful nitrogen-containing byproducts.

- **Fly ash reaction with Plant Root Exudates**: The interaction between plant root exudates (organic acids, enzymes) and fly ash in soil has not been well studied. These exudates could alter the 'chemical structure' and 'reactivity of fly ash', influencing its role in nutrient cycling and heavy metal mobility in soils.

Organic acids like citric acid or oxalic acid, secreted by plant roots, may dissolve minerals in fly ash, increasing the release of heavy metals or altering its pozzolanic properties.

$$CaCO_3 + 2C_6H_8O_7 \rightarrow Ca(C_6H_5O_7)_2 + CO_2 + H_2O$$

Enzymes secreted by plant roots may enhance the bioavailability of certain nutrients or trace metals trapped in fly ash.

IMPACT ON RETAINING WALL STABILITY

The above-mentioned geotechnical properties and chemical reactions of this have several detrimental

The above mentioned geotechnical properties and chemical reactions of this, have several detrimental effects on retaining wall stability. The following points are shows the impact on stability of retaining wall:

- **Increased Hydrostatic Pressure**: Poor drainage, 'characteristics of fly ash' backfill can lead to water accumulation, increasing hydrostatic pressure behind the retaining wall. This pressure can cause overturning or sliding failure of the wall.
- **Loss of Shear Strength**: Changes in moisture content and chemical composition of fly ash can reduce its shear strength, potentially leading to a loss of soil friction against the wall. This reduction in shear strength can result in a failure due to sliding or bearing capacity.
- **Structural Degradation**: Chemical reactions, such as ASR and sulfate attack, can degrade concrete and other wall materials, reducing their load-bearing capacity and 'increasing the likelihood' of failure [19].

MITIGATION MEASURES

To mitigate the 'detrimental effects of fly ash', backfill on retaining wall stability, the following measures can be considered:

- **Pre-Assessment of Fly Ash Properties**: Conduct thorough geotechnical and chemical analyses of the fly ash before use to determine its suitability as backfill. Assessments should focus on moisture sensitivity, compaction characteristics, potential for leaching, and chemical reactivity.
- **Use of Geosynthetics**: Geosynthetics such as geotextiles and geomembranes might be utilize to enhance drainage and provide a barrier between the fly ash backfill and the retaining wall, reducing the potential for chemical reactions.
- **Proper Compaction and Drainage Design**: Ensuring proper compaction of fly ash backfill and incorporating adequate drainage systems can help manage water infiltration and reduce 'hydrostatic pressure' 'behind the retaining wall'.
- **Chemical Treatment**: Adding lime or cement to fly ash can help stabilize the material, reduce its moisture sensitivity, and mitigate harmful chemical reactions. This stabilization process can also improve the shear strength and reduce the permeability of this material utilizing as backfilling [20].

FUTURE SCOPE

Fly ash have many potential applications in the coming 'research areas'. The chemical concerns for the fly ash using a combination of laboratory experiments, field studies, and advanced analytical techniques. Understanding the long-term 'chemical interactions' among 'fly ash' and materials will be crucial for predicting failure mechanisms and developing strategies to reduce these detrimental effects. Research on the fly ash from a chemistry perspective can focus on several key areas such as concrete and cement products, road base, oil stabilizer, clean fill, filler in asphalt, metal recovery, and mineral filler. However, 'fly ash' the 'by-product' of 'burning of coal' that contains small amounts of photoactive oxides like Fe_2O_3, CaO, and TiO_2. It has many potential applications, including as a photocatalyst for removal of toxic metal in water treatment applications. In the future work, we have explored the catalytic 'potential of fly ash' in degradation or transformation of emerging contaminants like waste water treatment. 'Fly ash' will be used as a support for photocatalyst in water treatment in different way such as removing pollutants from water, improving degradation efficiency, treating textile dye pollution, improving wastewater treatment.

References

1. Alam J., M. Akhtar, Fly ash utilization in different sectors in Indian scenario. Int. J. Emerg. Trends Eng. Dev. 2011, 1, 1–14.

2. Ohenoja, K.; Pesonen, J.; Yliniemi, J.; Illikainen, M. Utilization of Fly Ashes from Fluidized Bed Combustion: A Review. Sustainability 2020, 12, 2988.

3. Nisham, K.; Sridhar, M.B.; Kumar, V. Experimental study on class F fly ash cement bricks using partial replacement of fly ash by metakaolin. Int. J. Chem. Sci. 2016, 14, 227–234.

4. Yadav, V.K.; Pandita, P.R. Fly Ash Properties and Their Applications as a Soil Ameliorant. In Amelioration Technology for Soil Sustainability; Rathoure, A.K., Ed.; IGI Global: Hershey, PA, USA, 2019; pp. 59–89.

5. Yadav, V.K.; Fulekar, M.H. The current scenario of thermal power plants and fly ash: Production and utilization with a focus in India. Int. J. Adv. Eng. Res. Dev. 2018, 5, 768–777.

6. Yadav, V.K.; Choudhary, N. An Introduction to Fly Ash: Natural Nanostructured Materials; Educreation: New Delhi, India, 2019; Volume 1, p. 162.

7. Zhao, Y.; Soltani, A.; Taheri, A.; Karakus, M.; Deng, A. Application of Slag—Cement and Fly Ash for Strength Development in Cemented Paste Backfills. Minerals 2018, 9, 22.

8. Bingchuan Cheng, Rentai Liu, XiuhaoLi ,Enrique del Rey Castillo, Mengjun Chen ,Shucai Li Effects of fly and coal bottom ash ratio on backfill material performance, Construction and Building Materials Volume 319, 14 February 2022, 125831

9. Zhao, Y.; Soltani, A.; Taheri, A.; Karakus, M.; Deng, A. Application of Slag—Cement and Fly Ash for Strength Development in Cemented Paste Backfills. Minerals 2018, 9, 22.

10. Valentim, B.; Białecka, B.; Gonçalves, A.P.; Guedes, A.; Guimarães, R.; Cruceru, M.; Całus-Moszko, J.; Popescu, G.L.; Predeanu, G.; Santos, C.A. Undifferentiated Inorganics in Coal Fly Ash and Bottom Ash: Calcispheres, Magnesiacalcispheres, and Magnesiaspheres. Minerals 2018, 8, 140.

11. Choudhary, N.; Yadav, V.K.; Malik, P.; Khan, S.H.; Inwati, G.K.; Suriyaprabha, R.; Singh, B.; Yadav, A.K.; Ravi, R.K. Recovery of Natural Nanostructured Minerals: Ferrospheres, Plerospheres, Cenospheres, and Carbonaceous Particles From Fly Ash. In Handbook of Research on Emerging Developments and Environmental Impacts of Ecological Chemistry; Gheorghe, D., Ashok, V., Eds.; IGI Global: Hershey, PA, USA, 2020; pp. 450–470.

12. Ohenoja, K.; Pesonen, J.; Yliniemi, J.; Illikainen, M. Utilization of Fly Ashes from Fluidized Bed Combustion: A Review. Sustainability 2020, 12, 2988.

13. Fuller, A.; Maier, J.; Karampinis, E.; Kalivodova, J.; Grammelis, P.; Kakaras, E.; Scheffknecht, G. Fly Ash Formation and Characteristics from (co-)Combustion of an Herbaceous Biomass and a Greek Lignite (Low-Rank Coal) in a Pulverized Fuel Pilot-Scale Test Facility. Energies 2018, 11, 1581.

14. Wei, Q.; Song, W. Mineralogical and Chemical Characteristics of Coal Ashes from Two High-Sulfur Coal-Fired Power Plants in Wuhai, Inner Mongolia, China. Minerals 2020, 10, 323. Ceramics 2020, 3 410

15. Rodrigues, P.; Silvestre, J.D.; Flores-Colen, I.; Viegas, C.A.; Ahmed, H.H.; Kurda, R.; de Brito, J. Evaluation of the Ecotoxicological Potential of Fly Ash and Recycled Concrete Aggregates Use in Concrete. Appl. Sci. 2020, 10, 351.

16. S.S. Alterary and N.H. Marei Fly ash properties, characterization, and applications: A review Journal of King Saud University – Science 33 (2021) 101536

17. Alam, J.; Akhtar, M. Fly ash utilization in different sectors in Indian scenario. Int. J. Emerg. Trends Eng. Dev. 2011, 1, 1–14.

18. Langmann, B. Volcanic Ash versus Mineral Dust: Atmospheric Processing and Environmental and Climate Impacts. ISRN Atmos. Sci. 2013, 2013, 17.

19. Giménez-García, R.; Vigil de la Villa Mencía, R.; Rubio, V.; Frías, M. The Transformation of Coal-Mining Waste Minerals in the Pozzolanic Reactions of Cements. Minerals 2016, 6, 64

20. Zhao, Y.; Soltani, A.; Taheri, A.; Karakus, M.; Deng, A. Application of Slag—Cement and Fly Ash for Strength Development in Cemented Paste Backfills. Minerals 2018, 9, 22.