



A Study of Fly-Ash Utilization as Backfilling Material in Mines

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Abstract

The rapid growth of coal-based power generation has led to a substantial increase in fly ash production, particularly in countries like India where coal contains a high ash content (30–55%). The safe disposal and management of this by-product have become major environmental and logistical challenges due to the requirement of large ash ponds and the risk of air, soil, and water contamination. This study explores the potential of utilizing fly ash as a backfilling material in underground mines, presenting it as a sustainable and efficient solution for bulk ash utilization. Underground mine voids offer significant storage capacity and provide an opportunity to convert waste into a valuable resource. The research reviews the physical and chemical characteristics of fly ash and evaluates its suitability for mine backfilling applications. The backfilling process not only enables safe disposal of fly ash but also improves ground stability by supporting overlying strata and reducing surface subsidence. Additionally, it enhances mine safety and facilitates improved resource recovery. The study highlights various backfilling techniques, material preparation methods, and transportation systems used in fly ash utilization. Special emphasis is given to Indian conditions, where the integration of fly ash in mining and

construction sectors can significantly reduce environmental impacts while promoting sustainable development. The findings indicate that fly ash-based backfilling is a technically viable and environmentally beneficial approach that addresses both waste management and mining challenges. This approach contributes to circular economy principles by transforming industrial waste into a functional material for geotechnical applications. Overall, the study underscores the importance of adopting innovative strategies for fly ash utilization to achieve sustainable mining practices and environmental conservation.

Keywords:

Fly ash, Mine backfilling, Underground voids, Sustainable mining, Waste utilization, Ground stability



Introduction

Electricity is the backbone of modern civilization, underpinning industrial growth, urban development, and technological advancement worldwide. The global economy relies heavily on continuous and reliable energy supply, with coal remaining one of the most significant sources of power generation, particularly in developing nations. Since the early 20th century, coal-fired thermal power plants have played a dominant role in electricity production. However, this dependence has resulted in the generation of vast quantities of industrial by-products, notably fly ash, which presents serious environmental and disposal challenges (Ahmaruzzaman, 2010; World Coal Association [WCA], 2020). Fly ash is a fine particulate residue generated during the combustion of pulverized coal in thermal power plants.

During combustion, mineral impurities in coal melt and subsequently cool to form ash particles. The heavier fraction settles as bottom ash, while finer particles remain suspended in flue gases and are captured using electrostatic precipitators (ESPs) or similar devices. These fine particles, known as fly ash, primarily consist of silica, alumina, iron oxides, and trace elements, including potentially hazardous heavy metals (Vassilev et al., 2013; Ahmaruzzaman, 2010). Depending on the source of coal and combustion conditions, fly ash can exhibit significant variability in physical and chemical properties, influencing its potential applications (Blissett & Rowson, 2012).

India is one of the largest producers of coal-based electricity, ranking third globally after China and the United States. A distinguishing feature of Indian coal is its high ash content, typically ranging from 30% to 45%, compared to 10%–15% in imported coal. This results in the generation of substantial quantities of fly ash. According to the Central Electricity Authority (CEA), India generated over 217 million tonnes of fly ash in 2018–19, with continued growth in subsequent years due to increasing energy demand (Central Electricity Authority [CEA], 2025). The disposal of such massive volumes of fly ash poses considerable environmental and logistical challenges, requiring large land areas and careful management strategies (Central Pollution Control Board [CPCB], 2022).

Traditionally, fly ash has been disposed of in ash ponds or landfills, which occupy extensive land areas and pose environmental risks. It is estimated that tens of thousands of hectares in India are dedicated to ash disposal. These ash ponds can lead to soil degradation, groundwater contamination, and air pollution due to the dispersion of fine particles. The presence of heavy metals such as arsenic, mercury, cadmium, and lead further exacerbates environmental concerns, as these elements can leach into ecosystems and enter the food chain (Pandey & Singh, 2010; Qian et al., 2008). Additionally, airborne fly ash contributes to suspended particulate matter (SPM), which has adverse effects on human health and visibility (UNEP, 2019). In response to these environmental challenges, regulatory bodies and policymakers have introduced measures to promote the utilization of fly ash. In India, the Ministry of Environment, Forest and Climate Change (MoEFCC) has issued several notifications since 1994 mandating increased utilization of fly ash in various sectors. These initiatives have led to a significant rise in utilization rates, increasing from less than 10% in the 1990s to over 75% in recent years (MoEFCC, 2021; CPCB, 2022).

Despite this progress, a considerable proportion of fly ash remains unutilized, necessitating the exploration of innovative and sustainable applications (Gollakota et al., 2019). Fly ash has found widespread use in construction and civil engineering applications due to its pozzolanic properties. It reacts with calcium hydroxide in the presence of water to form cementitious compounds, enhancing the strength and durability of materials. Consequently, fly ash is extensively used in cement production, concrete manufacturing, road construction, and embankment stabilization (ACI Committee 232, 2003; Helmuth, 1987). High-volume fly ash concrete has been developed to reduce cement consumption and carbon emissions, contributing to sustainable construction



practices (Naik & Ramme, 1987; Chandra & Berntsson, 2002). Additionally, fly ash has been utilized in soil stabilization, agriculture, waste treatment, and advanced material synthesis such as geopolymers and zeolites (Davidovits, 2013; Yao et al., 2015).

In the field of geotechnical engineering, fly ash has demonstrated considerable potential as a construction and stabilization material. Its application in soil improvement enhances bearing capacity, reduces compressibility, and improves durability (Sivapullaiah & Moghal, 2011; Kumar & Gupta, 2018). The addition of lime or gypsum further enhances the strength characteristics of fly ash-based materials (Ghosh & Subbarao, 2007). Mechanical activation and processing techniques have also been explored to improve the reactivity and performance of fly ash in engineering applications (Temuujin et al., 2009). Among various utilization pathways, the application of fly ash in mine backfilling has emerged as a promising solution for bulk utilization. Mining operations, particularly underground mining, create voids that can compromise ground stability and lead to subsidence.

Backfilling involves placing material into these voids to provide structural support and enhance safety. Traditionally, sand, waste rock, and tailings have been used as backfill materials. However, the use of fly ash offers several advantages, including its availability, cost-effectiveness, and favorable engineering properties (Sahoo et al., 2016; Tripathy & Sahoo, 2015). The use of fly ash in mine backfilling aligns with sustainable development and circular economy principles by converting industrial waste into a valuable resource. Fly ash-based backfill can support overlying strata, reduce subsidence, and improve mine stability. It also helps in controlling mine fires and reducing environmental hazards associated with abandoned mine voids (Singh et al., 2018; Mandal et al., 2018). Furthermore, the large storage capacity of underground voids makes them ideal for the bulk disposal of fly ash, addressing one of the major challenges faced by thermal power plants (Li & Zhao, 2011; Zhang & Wang, 2007).

Table 1: Summary of Fly Ash Generation and Utilisation

No. of Plants (Data Available)	Total Capacity (GW)	Coal Consumption (LMT)	Total Generation (LMT)	Total Utilisation (LMT)	% Utilisation
189	214.06	8869.6	3187.98	3071.38	96.34

As per CEA report 2024-25

In India, the proximity of thermal power plants to coal mines presents a unique opportunity for the utilization of fly ash in mine backfilling. Pit-head power plants, which are located near mining areas, generate a significant portion of fly ash and can benefit from reduced transportation costs. According to recent reports, these plants contribute substantially to total fly ash generation and have considerable potential for utilization in mine filling and land reclamation activities (CEA, 2025; NTPC, 2023) Table 1 shows the overall generation and utilization of fly ash. The Indian Bureau of Mines (IBM) has also recognized the importance of backfilling in improving mine safety and environmental sustainability (IBM, 2020).

The effectiveness of fly ash as a backfill material depends on its classification and properties. Fly ash is generally categorized into siliceous (Class F) and calcareous (Class C) types based on its chemical composition. Siliceous fly ash exhibits pozzolanic properties, while calcareous fly ash possesses both pozzolanic and hydraulic characteristics. These properties influence the strength, permeability, and durability of the backfill material (IS 3812-1, 2013). The addition of binders such as cement or lime can further enhance the mechanical performance of fly ash-based backfills (Kumar et al., 2019). where as Figure 1 shows the sector wise utilization.



Fly Ash Utilisation Across Different Sectors

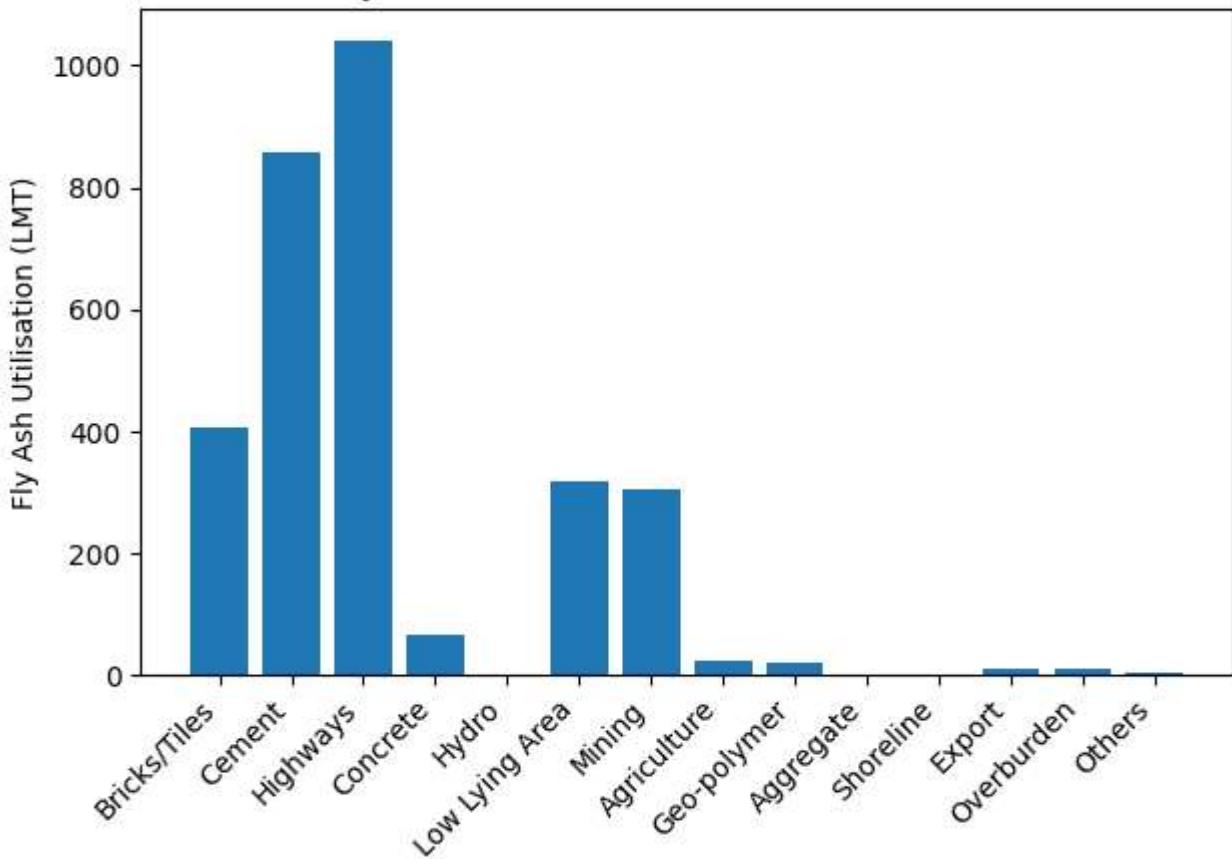


Figure 1 Fly ash utilisation across different sectors.

Advancements in ash handling technologies have improved the quality and usability of fly ash. Modern power plants employ dry ash collection systems, which facilitate the efficient recovery, storage, and transportation of fly ash. The fineness of fly ash, which increases with improved ESP performance, enhances its reactivity and suitability for engineering applications (Blissett & Rowson, 2012). These technological developments have expanded the scope of fly ash utilization in various sectors. Despite its potential, the use of fly ash in mine backfilling is not without challenges. Variability in ash properties, environmental concerns related to leaching of heavy metals, and logistical issues associated with transportation and handling must be carefully addressed. Long-term monitoring and proper design are essential to ensure the safety and effectiveness of fly ash-based backfill systems (Kumar et al., 2019; Qian et al., 2008). Geotechnical principles, such as those outlined in classical soil mechanics, play a crucial role in understanding the behaviour of backfill materials under different conditions (Terzaghi et al., 1996).

In recent years, there has been increasing emphasis on sustainable resource management and waste utilization. Organizations such as NTPC have implemented large-scale initiatives to promote fly ash utilization across multiple sectors, including mine backfilling, road construction, and land reclamation (NTPC, 2023). These efforts demonstrate the feasibility and benefits of integrating fly ash utilization into industrial and mining practices. Furthermore, global frameworks such as those promoted by the United Nations Environment Programme (UNEP) emphasize the importance of circular economy approaches in reducing environmental impacts and promoting sustainability (UNEP, 2019). In conclusion, the utilization of fly ash as a backfilling material in mines offers a viable and sustainable solution to the challenges of waste management and mine safety. It addresses critical issues such as land scarcity, environmental pollution, and ground instability while



contributing to resource efficiency and economic savings. The integration of fly ash into mine backfilling practices represents a significant step toward sustainable mining and environmental conservation. This study aims to explore the potential, challenges, and practical aspects of fly ash utilization in mine backfilling, with a particular focus on Indian conditions and current industrial practices.

2. Materials and Methods

2.1 Fly Ash

Fly ash is a finely divided residue generated during the combustion of pulverized coal in thermal power plants. Table 2 shows the chemical characteristics of fly ash. It is primarily an amorphous aluminosilicate material containing varying proportions of calcium compounds. During combustion, mineral matter present in coal melts and is carried along with flue gases. Upon cooling, this molten material solidifies into spherical particles, which are subsequently captured using electrostatic precipitators (ESPs) or mechanical separators.

Table 2. Chemical Characteristics of Fly Ash

Constituents	Percentage (%)
Carbon	1.85
Volatile Matter	0.16
Fe ₂ O ₃	8.23
MgO	0.84
Al ₂ O ₃	28.73
SiO ₂	57.91
P ₂ O ₅	0.11
SO ₃	0.14
K ₂ O	0.49
CaO	1.11
Na ₂	0.14
TiO ₂	0.29

Fly ash exhibits **pozzolanic properties**, meaning it reacts with calcium hydroxide in the presence of water to form cementitious compounds. Its chemical composition mainly includes oxides such as silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), iron oxide (Fe₂O₃), calcium oxide (CaO), magnesium oxide (MgO), potassium oxide (K₂O), and titanium dioxide (TiO₂). The relative proportions of these oxides vary depending on the type of coal, combustion temperature, and collection method. Table 3 Chemical Composition of Lime

Table 3. Chemical Composition of Lime

Constituent	Percentage (%)
Calcium Oxide (CaO)	97.6
Magnesium Oxide (MgO)	1.2
Silica (SiO ₂)	0.72
Ferric Oxide (Fe ₂ O ₃)	0.18
Aluminum Oxide (Al ₂ O ₃)	0.3

Physically, fly ash consists of very fine particles, typically ranging from 10 to 100 μm in diameter, with a predominantly spherical shape. It possesses low to medium bulk density, high specific surface area, and a relatively smooth texture, which enhances its workability in slurry form. The specific gravity of fly ash generally ranges between 1.6 and 3.1. The color varies from light grey to dark grey depending on the carbon content and



mineral composition. Fly ash particles predominantly fall within the silt-size range and are finer than ordinary Portland cement. Despite having a high surface area, fly ash exhibits relatively low cation exchange capacity (CEC) due to its non-plastic nature. However, its low water absorption characteristics make it suitable for applications such as soil stabilization and mine backfilling.

Classification of Fly Ash

Based on ASTM C618 standards, fly ash is broadly classified into two categories:

- **Class F Fly Ash:** Derived from the combustion of bituminous and anthracite coal, this type contains less than 10% calcium oxide. It exhibits pozzolanic properties and requires an external activator such as lime or cement to develop cementitious characteristics.
- **Class C Fly Ash:** Produced from sub-bituminous or lignite coal, this type contains more than 20% calcium oxide and possesses both pozzolanic and self-cementing properties. It does not necessarily require an activator for strength development.

The selection of fly ash type for mine backfilling depends on the required strength, setting time, and environmental conditions.

2.2 Lime

Lime, primarily in the form of calcium oxide (CaO), commonly known as quicklime, is widely used as a binding and activating agent in construction and geotechnical applications. It is a white, highly alkaline, and reactive material produced by calcination of limestone (CaCO₃). In the presence of water, quicklime undergoes hydration to form calcium hydroxide (Ca(OH)₂), releasing heat in the process. This hydrated lime acts as an activator for the pozzolanic reaction of fly ash, leading to the formation of cementitious compounds such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), which contribute to strength development. Lime plays a crucial role in fly ash-based backfilling systems by:

- Enhancing early strength gain
- Increasing pH, which immobilizes heavy metals
- Improving binding characteristics
- Reducing permeability

In the present study, mine water is used for slurry preparation, ensuring cost-effectiveness and resource optimization.

2.3 Methods of Mine Backfilling

The backfilling of underground mine voids using fly ash is typically carried out using slurry or paste-based techniques. The primary objective is to fill the voids created during mining operations, thereby improving ground stability, reducing subsidence, and enhancing mine safety. Figure 2. Flow chart of the process of backfilling in a underground mine's void.

2.3.1 Hydraulic Stowing Method (Fly Ash Slurry Backfill)

Hydraulic stowing is one of the most widely adopted methods for backfilling underground voids. In this method, fly ash and lime are mixed with water at the surface to form a slurry, which is then transported to underground voids through pipelines.

Process Steps:

1. **Mixing (Stirring Phase):** Fly ash is mixed with mine water in a typical proportion of 10:8 (fly ash: water by mass) in a mechanical mixer to form a homogeneous slurry.
2. **Pumping Phase:** The prepared slurry is transferred to a hopper and pumped through pipelines using a concrete pump. The pumping system ensures continuous and controlled delivery of slurry.
3. **Filling Phase:** The slurry is transported to underground voids (goaf areas) through main pipelines and branch pipes (10–20 m in length). The slurry flows into the void spaces and gradually settles.

4. Settling and Hardening: Excess water drains out and is often recycled. The deposited slurry begins to consolidate and harden within 24 hours, forming a solid mass that supports the surrounding rock strata.

Advantages:

- High flowability enables filling of irregular voids
- Reduced permeability due to fine particle packing
- Potential immobilization of heavy metals
- Reuse of excess water

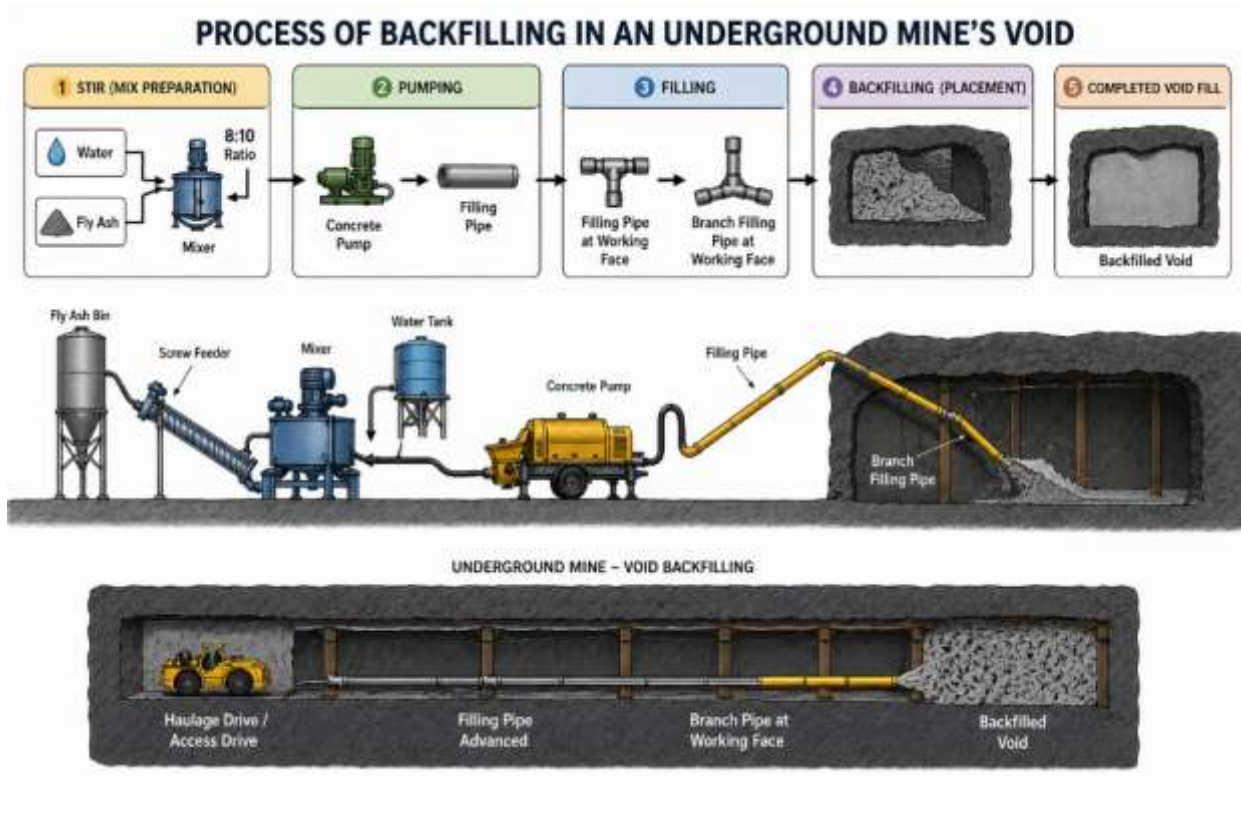


Figure 2. Flow chart of the process of backfilling in a underground mine’s void

2.3.2 High-Density Paste Backfill (HDPB)

In this method, fly ash, lime, and mine tailings are mixed to form a dense, non-segregating paste with low water content.

Key Features:

- High solids concentration
- Minimal bleeding and segregation
- Improved mechanical strength

Role of Materials:

- Fly ash acts as a fine filler and improves pumpability
- Lime activates pozzolanic reactions
- Tailings provide structural bulk

Advantages:

- Higher long-term strength (>90 days)
- Reduced water requirement
- Lower environmental impact



2.3.3 Fly Ash–Lime Slurry Backfill

This method is suitable for abandoned mines or areas where high strength is not the primary requirement.

Characteristics:

- High water content slurry
- Excellent flowability
- Ability to penetrate fine cracks and fissures

Applications:

- Sealing voids
- Fire control in coal mines
- Ground stabilization

2.3.4 All-Waste Backfilling Method

In this sustainable approach, a mixture of fly ash, bottom ash, and lime is used without relying on conventional aggregates.

Process:

- Fly ash acts as both binder and filler
- Lime activates pozzolanic reactions
- Bottom ash provides bulk

Benefits:

- Complete utilization of waste materials
- Suitable for mine closure and reclamation
- Reduces environmental footprint

2.4 Backfilling System Components

The backfilling system comprises the following subsystems:

2.4.1 Stirring System

- Fly ash storage bin
- Screw feeder
- Mechanical mixer

Fly ash is transported from the bin to the mixer using a screw feeder, where it is combined with water and lime to produce slurry.

2.4.2 Pumping System

- Hopper
- Concrete pump
- Delivery pipelines

The slurry is pumped under pressure to the underground voids.

2.4.3 Distribution System

- Main filling pipes
- Branch pipes (10–20 m length)

These pipes distribute the slurry evenly within the goaf area.



2.5 Technical Considerations

Curing and strength development, permeability and sealing and environmental considerations. The pozzolanic reaction between fly ash and lime is time-dependent and influenced by temperature. Higher temperatures, such as those found in deep mines, accelerate strength gain. Fine particles of fly ash reduce permeability, effectively sealing voids and preventing fluid migration. The high pH environment created by lime helps immobilize heavy metals, reducing leaching risks. Additionally, adsorption reactions with surrounding soil further limit contaminant transport.

3. Utilization of Fly Ash

3.1 Utilization of Fly Ash in the Construction Industry

Fly ash has emerged as a versatile and sustainable material in the construction sector due to its pozzolanic properties, fine particle size, and ability to enhance the performance of conventional materials. Its incorporation not only improves engineering properties but also contributes to environmental conservation by reducing the demand for natural resources. Figure 3 shows the overall fly ash utilization

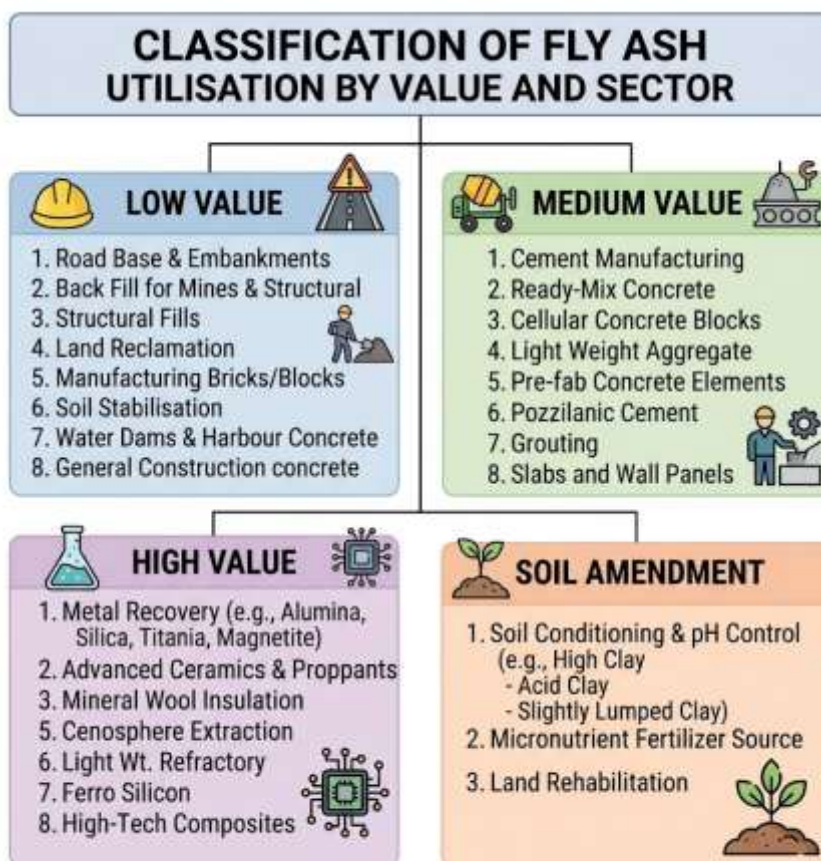


Figure 3 Overall fly ash utilization



3.2 Use of Fly Ash in Portland Cement Concrete

Fly ash is widely used as a supplementary cementitious material in Portland cement concrete. During cement hydration, calcium hydroxide is released, a portion of which remains unreacted. Fly ash reacts with this free lime in the presence of water to form additional cementitious compounds such as calcium silicate hydrate (C–S–H), which significantly enhances the strength and durability of concrete. The incorporation of fly ash in concrete leads to several improvements, including reduced bleeding, lower shrinkage, and decreased heat of hydration, making it particularly suitable for mass concrete applications. Additionally, it enhances workability and long-term strength while improving resistance to chemical attacks such as sulfate and alkali–silica reactions. From an economic perspective, fly ash reduces the overall cost of concrete by partially replacing cement. In India, the cement industry utilized approximately 60 million tonnes of fly ash during 2018–19, highlighting its large-scale adoption.

3.3 Fly Ash in Bricks, Blocks, and Tiles

The use of fly ash in the manufacturing of bricks, blocks, and tiles presents a dual advantage of waste utilization and conservation of topsoil. Fly ash bricks are produced by blending fly ash with lime, gypsum, and sand, followed by compaction and curing. These bricks exhibit higher compressive strength, lower water absorption, and improved durability compared to conventional clay bricks. Fly ash-based construction products are also lightweight, thermally efficient, and possess uniform shape and smooth surfaces, which reduce mortar consumption. Over the years, the use of fly ash in brick manufacturing has increased significantly, rising from less than 1 million tonnes in the late 1990s to over 20 million tonnes in recent years. Additionally, fly ash is used in the production of ceramic tiles, paving blocks, and prefabricated panels, offering cost-effective and environmentally friendly alternatives. Organizations such as NTPC have actively promoted fly ash brick manufacturing by establishing production units and supplying ash free of cost to brick manufacturers, thereby encouraging its widespread use.

3.4 Fly Ash in Stabilized Base Courses

Fly ash plays an important role in the construction of stabilized base courses for roads. It is typically mixed with lime or Portland cement and aggregates in controlled proportions to form pozzolanic stabilized mixtures. A common mix includes approximately 12–14% fly ash and 3–5% lime. These mixtures exhibit properties similar to cement-stabilized bases, providing high strength, durability, and resistance to deformation. The use of fly ash in base courses reduces construction costs and allows the use of conventional construction equipment. However, proper attention must be given to curing conditions, seasonal variations, and surface protection to ensure long-term performance.

3.5 Fly Ash in Pavement Applications

In pavement engineering, fly ash is commonly used as a filler material in asphalt mixes. Its inclusion improves the stiffness and rutting resistance of asphalt concrete while enhancing durability. Fly ash also reduces stripping potential by improving the bond between aggregates and bitumen. Additionally, fly ash slurry can be injected beneath existing pavements to fill voids and provide structural support. This technique is particularly useful for pavement rehabilitation and maintaining grade stability. Its economic advantage and ease of application make it a preferred material in infrastructure projects.



3.6 Fly Ash Utilization in Geotechnical Engineering

Fly ash has gained significant importance in geotechnical engineering due to its ability to improve soil properties, enhance strength, and provide cost-effective alternatives to conventional materials.

3.7 Fly Ash as a Replacement for Earthen Backfill (Flowable Fill)

Flowable fill, also known as controlled low-strength material (CLSM), is a self-compacting and self-leveling mixture consisting of fly ash, water, cement, and sometimes aggregates. It is used as a substitute for conventional earthen backfill in applications such as retaining walls, bridge abutments, and underground structures.

The advantages of flowable fill include ease of placement, reduced labor requirements, and elimination of compaction efforts. It provides higher strength and durability compared to traditional backfill materials while reducing maintenance costs. The strength of the material depends on the proportion of cementitious components, with Class C fly ash mixtures generally exhibiting higher strength due to their higher calcium content.

3.8 Fly Ash in Embankments and Structural Fills

Fly ash is widely used in the construction of embankments and structural fills as a substitute for natural soil. When properly designed and compacted, fly ash-based fills offer comparable or superior performance to conventional materials.

The design of such fills requires careful consideration of factors such as moisture content, particle size distribution, shear strength, and compressibility. Dry (silo-collected) fly ash is generally preferred over pond ash due to its better quality and uniformity. Laboratory testing is essential to evaluate the engineering properties and ensure suitability for specific applications.

Fly ash embankments are lightweight, which reduces the load on underlying soils, making them particularly suitable for weak subgrades. However, issues such as frost susceptibility and drainage must be addressed through proper design measures, including the use of geotextiles.

3.9 Fly Ash for Stabilization of Expansive Soils

Expansive soils are characterized by significant volume changes due to variations in moisture content, which can lead to structural damage. Fly ash is an effective stabilizing agent for such soils.

When mixed with soil, fly ash reduces plasticity and improves strength by promoting flocculation and agglomeration of soil particles. The presence of lime in fly ash further enhances stabilization through pozzolanic reactions. Typically, an addition of 12–15% fly ash is sufficient to achieve significant improvement in soil properties.

The stabilization mechanism involves a transformation of soil texture from clay-like to silt-like behaviour, resulting in reduced swelling potential and improved load-bearing capacity.

3.10 Fly Ash in Agriculture and Land Reclamation

Fly ash has also found applications in agriculture and land reclamation. When applied in controlled quantities, it improves soil texture, porosity, and nutrient availability, making it suitable for degraded lands. Collaborative research projects have demonstrated its potential in enhancing crop productivity and soil health.

In mining areas, fly ash is extensively used for filling abandoned mine voids, facilitating land reclamation and ecological restoration. This application not only addresses disposal challenges but also enables the reuse of degraded land for productive purposes.



3.11 Fly Ash in Infrastructure and Transportation

Fly ash plays a critical role in infrastructure development, particularly in road construction and embankment formation. It improves the strength and stability of subgrades and reduces the thickness of pavement layers. Large-scale utilization in national highway projects has demonstrated its economic and technical feasibility. Innovative approaches, such as the use of bottom ash as a partial replacement for natural sand in concrete, have also been successfully implemented in infrastructure projects. These advancements highlight the growing importance of fly ash in sustainable construction practices.

3.12 Transport and Handling Innovations

Efficient transportation and handling systems are essential for large-scale utilization of fly ash. Modern approaches include bulk transport through rail wagons, inland waterways, and pneumatic conveying systems. These methods reduce environmental impact and ensure cost-effective delivery. Recent innovations such as electric bulk transport vehicles and high-concentration slurry pipelines further enhance sustainability by reducing carbon emissions and improving operational efficiency. Government policies, including freight subsidies and mandatory utilization norms, have also played a significant role in promoting fly ash usage.

3.12 Emerging Research and Development

Ongoing research and development efforts are focused on expanding the applications of fly ash in advanced materials and sustainable construction technologies. Innovations such as geopolymer concrete, lightweight aggregates, and nano-engineered construction materials are gaining attention. Geopolymer technology, in particular, offers significant environmental benefits by reducing carbon emissions associated with traditional cement production. Demonstration projects in India have shown promising results, indicating the potential for large-scale adoption.

Conclusion

The continuously rising global demand for electricity, particularly in developing nations such as India, indicates that coal-based power generation will remain a significant contributor to the energy mix in the foreseeable future. As a direct consequence, the generation of fly ash is expected to increase substantially. This creates a dual challenge: the requirement of vast land areas for disposal and the associated environmental risks, including air, soil, and groundwater contamination. Although India has made notable progress in fly ash management, achieving a utilization rate of around 77–78%, there remains a critical need to move towards 100% utilization through the adoption of innovative, large-scale, and sustainable applications. This study highlights that fly ash is no longer merely a waste by-product but a valuable industrial resource with diverse applications in construction, geotechnical engineering, agriculture, and infrastructure development. Its use in cement, concrete, bricks, embankments, and soil stabilization has already demonstrated significant economic and environmental benefits. However, among all potential applications, the utilization of fly ash in mine backfilling stands out as a highly promising solution for bulk consumption. The research presented in this work focuses on the development and field implementation of a fly ash–lime water slurry as a backfilling material for underground mine voids. The findings clearly indicate that this method is effective in controlling the movement of overlying strata, thereby significantly reducing surface subsidence. Additionally, the technique enables the safe extraction of coal from barrier pillars, which would otherwise remain unmined due to stability concerns. The use of pipeline transportation and slurry-based grouting further enhances operational efficiency and feasibility in underground conditions. The fly ash–lime slurry system offers multiple advantages: it improves ground stability, reduces permeability, minimizes environmental hazards through immobilization of contaminants, and promotes the



reuse of industrial waste. Furthermore, it provides an economically viable alternative to conventional backfilling materials, reducing both material and operational costs. By utilizing mine voids as repositories for fly ash, this approach effectively addresses the twin challenges of waste disposal and mine safety.

From a broader perspective, the integration of fly ash utilization into mining and infrastructure practices aligns strongly with the principles of sustainable development and circular economy. It reduces dependence on natural resources, minimizes environmental degradation, and enhances resource efficiency. However, achieving large-scale implementation requires coordinated efforts from government agencies, industry stakeholders, and researchers. Policy support, technological advancements, and awareness initiatives will play a crucial role in expanding the scope of fly ash utilization. In conclusion, the use of fly ash, particularly in the form of lime-activated slurry for mine backfilling, represents a technically feasible, environmentally sustainable, and economically beneficial solution. With continued research, innovation, and policy support, fly ash can be effectively transformed from an environmental liability into a strategic resource, contributing significantly to sustainable mining practices and overall environmental management.

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