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Review paper

USE OF FLY ASH IN ROAD CONSTRUCTION

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Abstract

Fly ash is a by-product of coal combustion in thermal power plants. While the European Union recycles and utilizes almost all of its fly ash across various industries, only 2.7% is used in our country. This paper researches the potential applications of fly ash in road construction, including its use in embankment layers, enhancement of mechanical properties, soil stabilization, and as a filler replacement in asphalt mixtures. Research has shown that the use of fly ash can significantly reduce road construction costs, ranging from 30% to 80%.The paper also researches the technical, ecological, and economic aspects of fly ash utilization in infrastructure projects.

Key words: fly ash, road construction, embankment, pavement construction, asphalt mixture

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1. INTRODUCTION

Fly ash, generated by the combustion of fossil fuels in thermal power plants, presents a significant environmental challenge due to its high concentration of harmful substances. However, the implementation of electrostatic filtration systems allows for efficient removal of ash particles from flue gases, thereby reducing the environmental impact. This process produces fly ash, which can be repurposed for various industrial applications.

Utilizing fly ash in industry not only reduces waste generation but also contributes to the sustainability of production processes across different sectors. Notably, the application of fly ash in road construction offers several advantages, including:

- **Reduction of environmental impact**: Fly ash use limits the need for natural materials and reduces landfill burdens.
- **Improvement of soil properties**: Fly ash can enhance the mechanical behavior and bearing capacity of subgrade soils.
- **Increased material strength**: When properly mixed, fly ash contributes to stronger, more durable structural layers.
- **Conservation of natural resources**: By substituting fly ash for conventional materials like cement and lime, the consumption of non-renewable resources is decreased.
- **Economic benefits**: Fly ash is typically more cost-effective than traditional construction materials, leading to significant financial savings in large-scale projects.

2. FLY ASH – GENERATION PROCESS AND CLASSIFICATION

The formation of fly ash is directly associated with the combustion of coal in thermal power plants. The generation process is as follows:

- **Combustion Process and Ash Formation**: Fly ash is primarily generated during coal combustion in power plant boilers for electricity production. The combustion process involves complex chemical and physical transformations, including heat release, conversion of organic and inorganic components in coal, and the creation of combustion by-products, among which ESP fly ash is a major constituent.
- **Chemical Composition of Fly Ash**: Fly ash consists of fine, spherical particles that are carried by flue gases during combustion. Its composition depends on the type of coal burned, combustion conditions, and the type of power plant. Common components of fly ash include silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3), calcium oxide (CaO), and unburnt carbon.
- **Separation of Fly Ash**: As the flue gas containing ash travels through the boiler and enters the gas purification system, fly ash particles are separated from the gas stream. Various collection devices, such as electrostatic precipitators or bag filters, are used to capture the fine particles before the gas is released into the atmosphere.

As shown in Figure 1, which illustrates the generation of fly ash in a thermal power plant boiler, approximately 20% of the total ash is removed from the boiler as bottom ash, while 80% is collected from flue gases via electrostatic filters—this fraction constitutes fly ash.

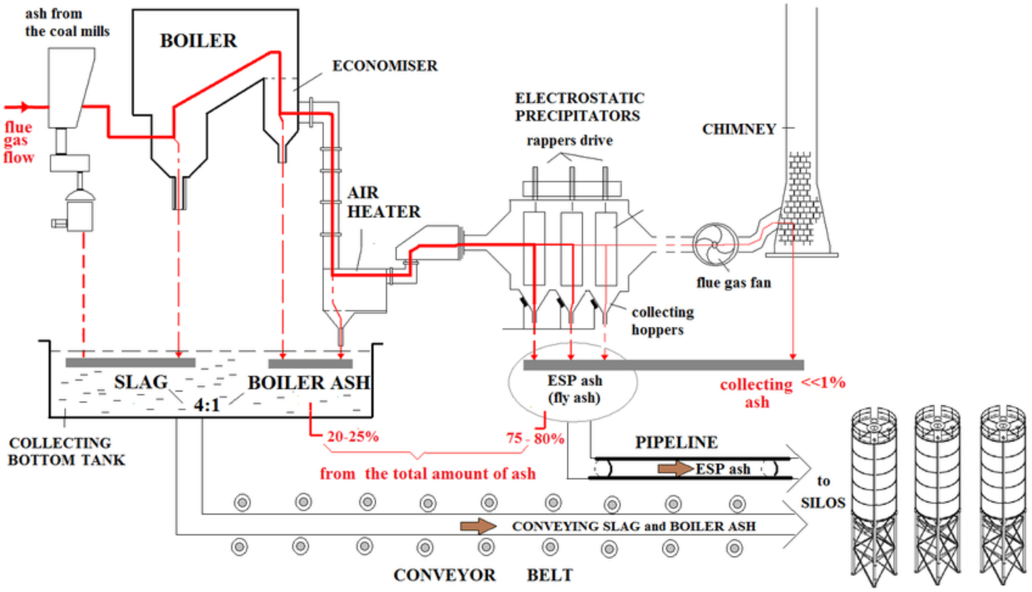

Figure 1 -Distribution of slag and ash in a typical thermal power plant [1]

- **Classification of Fly Ash:** Fly ash is categorized into two main types: Class F and Class C. Class F fly ash is derived from the combustion of anthracite or bituminous coal and is characterized by a low calcium oxide content. In contrast, Class C fly ash is produced from the combustion of sub-bituminous or lignite coal and contains a higher proportion of calcium oxide. The type of fly ash significantly influences its properties and potential applications [2,3,4].

3. APPLICATION IN ROAD CONSTRUCTION

Fly ash has long been used in concrete production both in the European Union and in our country; however, in Europe and the United States, a significant amount is also used in road construction. In the EU, countries do not face issues with fly ash disposal—out of 18 million tons of fly ash produced in 15 EU member states, 14 million tons are consumed in concrete production, while approximately 23% is used in road construction [5]. In contrast, in our country, only 2.7% of the produced fly ash is utilized, and solely for concrete production; it is not used at all in road construction, despite the fact that its application in subgrade layers could reduce construction costs by 30% to 80% [5].

In road construction, fly ash can be used in embankments, road subgrades, lower bearing layers of pavement structures, asphalt mixtures, utility trench backfills, mechanical property improvement, soil stabilization, and the rehabilitation of degraded areas.

Figure 2 illustrates the percentage of fly ash utilized in the production of various construction materials and structures in the year 2006.

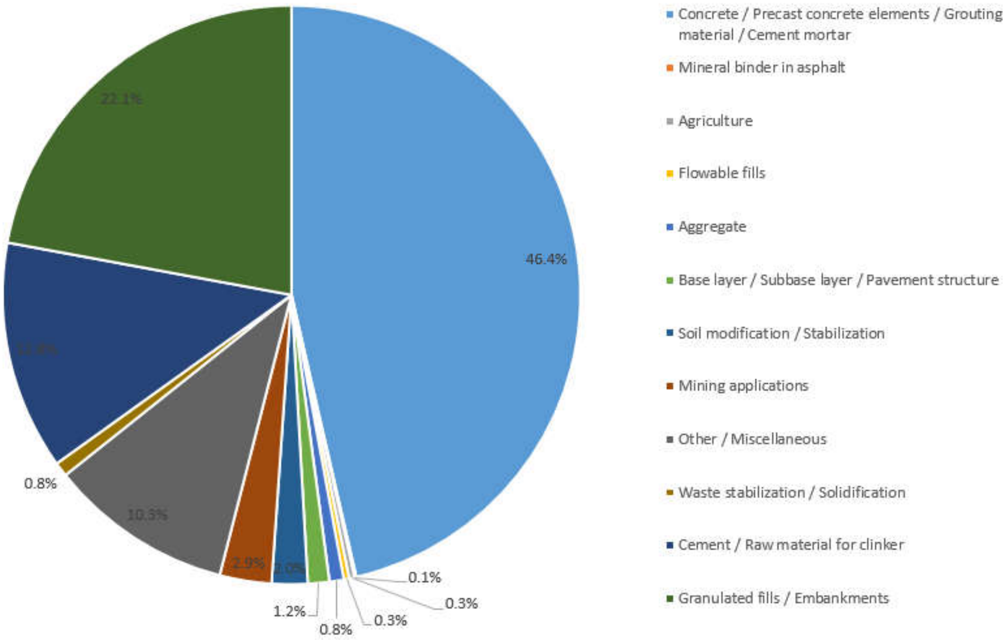

Figure 2 - Standard application of fly ash

3.1. Application in Embankments or Fill Material

According to data from the American Coal Ash Association, the second most widespread use of fly ash, after its application in concrete production, is in embankment and fill construction. The use of this material in embankments and granular fills gained momentum in the 1950s in the United Kingdom, where it was employed as an alternative borrow material for the subgrade of railway lines [6].

The standard guide for the design and construction of granular fills with fly ash, ASTM E2277-03, recommends the use of this material in embankments and backfills. Fly ash offers several advantages over traditional soil or stone materials, including relatively low specific weight, high shear strength, easy handling and compaction, and economic viability in regions where it is readily available. Due to its low specific gravity, it can be placed over weak or soft subgrade soils, while its high shear strength minimizes settlements. When placed at optimum moisture content, compaction is significantly faster compared to natural soils.

Over a period of more than three years, the behavior of two fly ash embankment projects (in the U.S. states of Delaware and Pennsylvania) was monitored during both construction and operational phases. During this period, no evidence of excessive settlement or negative environmental impact was observed [7].

The optimal moisture content for fly ash in embankment construction is between 3% and 4%, and the material should be delivered to the site in this condition [7].

The most important technical properties of fly ash include:

- Shear strength
- Moisture-density relationship (compaction curve)
- Unconfined compressive strength
- Gradation (particle size distribution)
- Consolidation characteristics
- Hydraulic conductivity

Design calculations for embankments using fly ash follow the same procedures as those used for natural soil. Such embankments will have comparable strength and compaction properties but lower dry density. Fly ash embankment bases should not be exposed to moisture, wet soil, or areas with a high groundwater table. A practical method to prevent capillary rise or seepage in fly ash embankments or backfills is to install a drainage layer of coarse crushed material at the base [8].

Additionally, erosion control must be considered. Slopes should be protected immediately after embankment construction to reduce runoff-induced erosion from water or strong winds. One method is to construct coarse-soil cells over the slope surface and fill them with fly ash. These cells act as barriers that reduce the kinetic energy of water and prevent the washing out of fine particles [6].

Another effective method is to apply topsoil and vegetation cover. The bearing capacity of the subgrade is expressed similarly to standard embankments, using the California Bearing Ratio (CBR) for flexible pavements or the subgrade reaction modulus (K) for rigid pavements.

Construction should be suspended during severe weather conditions such as heavy rainfall, snowstorms, and prolonged periods of freezing temperatures. It is not recommended to place and compact fly ash at ambient temperatures below -4°C [6]. As previously mentioned, freeze–thaw cycles do not significantly affect the strength of fly ash, allowing for ice expansion without compromising material integrity [9]. However, replacing frost-resistant soil with fly ash in frost-susceptible zones may introduce performance issues [6].

3.2. Application in Stabilized Subbase and Subgrade Layers

Fly ash can also be used for the construction of stabilized subbase and subgrade layers. Both fully bitumenized fly ash (Class F) and partially bitumenized fly ash (Class C) can be applied. Class F fly ash requires the addition of chemical reagents (activators), aggregates, and water to achieve the desired binding properties, whereas Class C fly ash typically does not require chemical additives due to its self-cementing characteristics [6].

For coarser aggregates, the required amount of fly ash is lower compared to that needed for finer aggregates.

In the late 1950s, a pavement base layer mixture called "Poz-o-Pac" was patented. It consists of a combination of lime, fly ash, and aggregates. All mixtures containing fly ash can generally be categorized as pozzolan-stabilized bases (PSB), where the aggregate serves as the main component [6].

A similar application of fly ash as a binder layer is the cold in-place recycling (CIR) method. This process involves milling and crushing the existing pavement layer, mixing it with an asphalt emulsion as a stabilizer, and reapplying it on-site. This creates a reliable base for a new pavement layer and, in some cases, serves as a final layer itself. Replacing the asphalt emulsion with fly ash in this method can yield similar results [10].

Research in the United States has shown that fly ash performs well in stabilizing subbase layers under low-traffic conditions such as access roads, parking lots, and sidewalks.

Adding 10% to 20% of Class C fly ash to the top layer of embankments or subgrade soil improves unconfined compressive strength and CBR values. Additionally, reducing the time between soil compaction cycles when fly ash is present positively affects subgrade bearing capacity.

Class C fly ash has been successfully used in soil stabilization tests at two construction sites in Wisconsin. Both subgrades consisted of more than 90% fine-grained aggregates with in-situ moisture contents 6% to 7% above the optimum. CBR values were initially low (between 1 and 3). At both sites, stabilization with self-cementing fly ash significantly improved soil strength and stiffness. The increased stiffness enhanced load-bearing capacity and reduced deformation under construction traffic. Laboratory tests showed improved unconfined compressive strength, higher CBR values, and better resilient modulus (Mr) of the soil after fly ash addition. Mixing more than 20% fly ash resulted in diminished improvements, while mixtures with 10% to 12% fly ash provided optimal cost-efficiency and mechanical performance. Field-measured CBR values for the optimal mixture were about two-thirds of those recorded in the lab—sufficient to support construction equipment loads [11].

3.2.1. Design Considerations

Once the particle size distribution of the pozzolanic stabilization mixture is determined, it is necessary to quantify the fraction smaller than 0.063 mm. This is assessed using the Proctor compaction test at the optimal moisture content. After determining the gradation, the next step is to establish the ratio of activator to fly ash in the mixture. Based on the results of strength and durability tests on a series of trial samples—and in accordance with ASTM C593 procedures—the optimal mixture composition is defined [12].

Typically, the combined content of fly ash and activator ranges between 12% and 30% of the total mixture mass. The most cost-effective composition is usually the one with the lowest amount of activator in the finest fraction, provided it still meets the required strength and durability criteria. For safety reasons, pozzolanic stabilization intended for field application must include at least 0.5% more activator than the amount determined in the optimal lab mixture [13].

Parameters such as CBR, unconfined compressive strength, and resilient modulus (Mr) generally increase up to 5% with the addition of cement. However, increasing the lime content has shown an opposite effect.

Structural design of pavement systems with stabilized subbase layers incorporating fly ash follows the same methodology used for conventional pavement structures and adheres to AASHTO standards.

3.2.2. Construction and Handling Procedures

When constructing and placing self-cementing fly ash mixtures, attention must be paid to the following:

- **Uniform distribution of fly ash** within the mixture;
- **Proper pulverization and thorough mixing** of fly ash with the subgrade material;
- **Moisture control** to achieve maximum dry density and strength;
- **Final compaction** within the prescribed time frame [14].

Pozzolanic stabilization can be carried out either in a plant or directly on-site. Plant mixing enables precise control of composition and material homogeneity, which improves the quality of the final mixture. The process may be batch-based, using a rotating drum, or continuous, where calibrated quantities of aggregate, fly ash, and activator are mixed in cycles of 30–45 seconds [15]. The mixture is then transported to the construction site and placed using bulldozers or pavers, allowing for controlled layer thickness and moisture content.

On-site mixing is commonly used in pavement recycling. Although the mixture may be less uniform compared to plant mixing, high-quality material can still be achieved. Fly ash is spread directly onto the subgrade or aggregate layer, followed by the addition of activator and in-place mixing. Maintaining optimal moisture levels is critical—excess water can hinder workability and reduce stabilization efficiency.

Class C fly ash must be compacted within two hours of placement to prevent loss of strength [16,17]. Compacted pozzolanic stabilization layers should be no thinner than 100 mm and no thicker than 200–225 mm in their final compacted state. Loose layers should be spread about 50 mm thicker than the required compacted thickness. The surface of each compacted layer should be scarified before the next layer is placed [6].

After placement and compaction, the stabilized material must be protected from drying out to allow it to gain sufficient strength. This can be achieved by water curing or applying an asphalt emulsion before placing the final pavement layer. If asphalt surfacing is planned, it is recommended to install it within 24 hours. Opening the section to traffic before placing the surface layer is permitted only after the stabilized base layer reaches a compressive strength of 2410 kPa, which typically occurs within 7 days [13].

Base layers stabilized with fly ash are less likely to develop reflective cracking compared to those stabilized with Portland cement, due to weaker intermolecular bonding. Field and laboratory tests have shown that layers stabilized with fly ash or lime are generally less prone to cracking and shrinkage than those stabilized with cement [18]. On some test sections using mixtures of cement and fly ash, cracking was observed due to lower density and strength, whereas studies conducted in Wisconsin indicated that sections stabilized with fly ash alone performed better over time [19,20].

3.3. Application in Asphalt Layers

Asphalt mixtures are composite materials made of bitumen and mineral aggregate, used primarily for road construction. The most common method of production is hot mix asphalt (HMA), in which the aggregate is heated to approximately 150°C and the bitumen to around 90°C before mixing.

Fly ash can be used as a mineral filler in these mixtures, filling voids and binding coarser aggregate particles. This approach not only reduces the amount of fly ash disposed of in landfills, but also lowers material costs [21]. Typically, fly ash is added in small quantities (around 5% by dry mass). Asphalt mixtures containing fly ash exhibit performance characteristics similar to those using conventional fillers such as limestone powder [22].

Fly ash can also partially replace bitumen in proportions ranging from 10% to 30%, without significantly compromising the strength and durability of the mixture [23,24]. Due to its lower specific gravity, it increases the volume of the binder phase, which can enhance mixture economy and longevity. However, additional field testing is needed to confirm long-term performance.

Fly ash has also been successfully used as a substitute for stone dust in asphalt concrete mixtures, due to its comparable physical properties. Its hydrophobic nature reduces the stripping of bitumen from the surface of aggregate particles, improving the water resistance and durability of the pavement.

Early studies, dating back to 1931, demonstrated that fly ash could effectively fill voids in asphalt mixtures and improve stability. More recent evaluations, including those by the U.S. Federal Highway Administration (FHWA), confirmed that asphalt mixtures containing fly ash exhibit greater resistance to moisture damage and stripping compared to those using other fillers like limestone or silica flour [25,26].

Testing conducted at North Dakota State University further indicated that lignite-based fly ash increases the strength and abrasion resistance of asphalt mixtures, especially when used in combination with cement or lime [27].

As of 2006, over 29 million tons of fly ash had been used as filler in asphalt across the United States, with most states reporting satisfactory results [28]. This broad application underscores the potential of fly ash as an economical and environmentally friendly alternative that enhances both durability and performance of asphalt pavements.

For fly ash to be used as an asphalt filler, it must be completely dry. Therefore, moistened fly ash or ash from storage lagoons is not suitable. In thermal power plants, fly ash is collected and stored in sealed, moisture-proof silos, ready for transport and use in asphalt concrete production.

4. CONCLUSION

The use of electrostatic precipitator fly ash in road construction offers significant benefits in terms of ecological sustainability, economic efficiency, and performance improvements for road infrastructure. As a by-product of thermal power plants, fly ash can serve as an alternative material for embankments, stabilization of subbase layers, and enhancement of asphalt mixtures. Literature confirms that the addition of fly ash improves the mechanical properties of asphalt, including its resistance to deformation and increased load-bearing capacity.

This material contributes to the reduction in the use of natural resources such as cement and lime, which lowers CO2 emissions and promotes sustainable construction practices. The economic advantages of fly ash are also evident, as it is often more affordable than conventional materials, leading to significant cost savings in large-scale construction projects.

Moreover, fly ash mixtures have shown higher resistance to water and freezing, which is crucial for the durability of roads in diverse climatic conditions.

The power utility EPS possesses large quantities of fly ash that could be used for road infrastructure development, potentially even for a 2,000-kilometer highway. EPS had previously been exempt from paying an environmental tax on each ton of ash, representing a significant financial saving. However, fly ash storage sites in Serbia cover 1,400 hectares, and EPS spends around 50 million euros annually on maintaining these deposits. Compared to traditional materials, the use of fly ash in construction could save between 30% and 80%. While fly ash has been successfully used for road construction in countries like the Netherlands and the Czech Republic, its application remains limited in Serbia. For example, during the construction of the Belgrade-Čačak highway, the contractor failed to meet the technical specifications for embankments made from fly ash, leading to the rejection of the donated fly ash. Additionally, fly ash could become an export product, especially for markets in the Middle and Far East. However, additional investments in infrastructure and facilities would be required for export.

In conclusion, the use of electrostatic precipitator fly ash in road construction represents a sustainable and economical alternative to traditional materials, with proven improvements in performance and a reduced environmental impact.

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