

Utilization of Fly Ash in the Cement Industry: A Sustainable Construction Approach

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Abstract: - Lignite fly ash from the Kosovo B thermal power plant is a major industrial by-product that can be used as a supplementary cementitious material (SCM). Through a comprehensive two-year monitoring program in 2024 and 2025, this paper presents a study of lignite fly ash from the Kosovo B thermal power plant. The study showcases and monitors its chemical traits, mechanical performance and industrial viability. This study, through the use of X-ray fluorescence (XRF) analysis, found that fly ash contains an average of 32.28% SiO_2 , 9.01% Al_2O_3 , 6.76% Fe_2O_3 , and 32.93% CaO , with a loss on ignition (LOI) of 2.88%. These characteristics are comparable to Class C fly ash according to the classifications of ASTM C618 and EN 450-1. Regarding average compressive strengths, they reached 14.66 MPa at 7 days and 35.14 MPa at 28 days. Statistical analysis revealed variations over the two years; notably, moisture content negatively impacted early strength ($r = -0.547$), while MgO exhibited a moderate negative correlation with 28-day strength ($r = -0.411$). These results are consistent with high-calcium fly ashes reported in international studies. The benefits of greater use of this material include a reduction in clinker demand, conservation of raw materials, and support for the reuse of industrial by-products in cement production.

Key-Words: - Fly ash, Supplementary cementitious material, Compressive strength, XRF analysis, clinker replacement, Sustainability.

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1 Introduction

Lignite remains one of the most important fuels for electricity generation worldwide due to its relatively low cost and wide availability. Kosovo is an example of this reality, as through the Kosovo A and Kosovo B power plants, lignite supply is responsible for 97% of the country's electricity production, [1]. With lignite also comes its by-product: combustion creates large quantities of fly ash, which makes its management and valorisation particularly important from both an environmental and economic point of view, [2]. These by-products need to be treated accordingly, as their improper disposal can result in contamination of soil and groundwater, [3], [4]. The cement industry contributes around 7-8% of global anthropogenic carbon dioxide (CO_2) emissions, leading to it being considered one of the most carbon-intensive industrial sectors, [5], [6]. The majority of these

emissions result from clinker production, mostly during the calcination of limestone and the combustion of fossil fuels required for high-temperature processing. Therefore, an effective strategy that has reduced both energy consumption and carbon emissions has been tied to the partial replacement of clinker with supplementary cementitious materials (SCMs). Fly ash, among the various SCMs, is commonly studied for its chemical and mineralogical properties, as its particles contain reactive amorphous silica and alumina phases that take part in pozzolanic reactions with calcium hydroxide released during cement hydration. As a result, these reactions produce additional calcium silicate hydrate (C-S-H) gel, which contributes to microstructural densification, improved mechanical strength, reduced permeability, and enhanced durability of cementitious materials, [7], [8]. The chemical

composition, particularly the contents: SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , and SO_3 , strongly influence the performance of fly ash in cement-based systems, [9], [10].

High-calcium (Class C) fly ashes generally exhibit higher hydraulic activity and may contribute to both early-age and long-term strength development compared with low-calcium (Class F) fly ashes, [11], [12]. Numerous studies have demonstrated that the incorporation of fly ash positively impacts long-term mechanical performance, enhances durability, and reduces the environmental footprint of concrete and cement products, [13]. Although extensive international research has been conducted on the utilization of fly ash in cementitious systems, limited information is available regarding the long-term chemical stability and mechanical performance of lignite fly ash generated by the Kosovo B thermal power plant under industrial operating conditions. Existing studies related to Kosovo lignite have primarily focused on combustion processes, environmental impacts, and emission monitoring, while investigations linking fly ash composition with mechanical performance remain scarce, [1], [2]. This study evaluates the chemical composition, variability, and compressive strength of fly ash collected from the Kosovo B thermal power plant during the 2024–2025 monitoring period.

Major oxide compositions were determined using X-ray fluorescence (XRF) analysis, while compressive strength testing and statistical correlation analysis were applied to investigate the relationships between chemical composition and mechanical behaviour. Furthermore, the obtained results were compared with international literature data in order to assess the suitability of Kosovo B fly ash as a supplementary cementitious material for sustainable cement production and clinker replacement applications.

1.1 Research Objectives

The objective of this study is to measure and showcase the suitability of lignite fly ash generated at the Kosovo B thermal power plant, for use as a supplementary cementitious material (SCM) in cement production, by promoting the beneficial use of industrial by-products [3], [13], [14]. Entering in detail, the specifics of the study objectives are: determination of the chemical composition of Kosovo B fly ash using X-ray fluorescence (XRF) analysis, placing particular emphasis on the major oxides relevant to cement production including: SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , and SO_3 and lastly the classification of the investigated fly ash

according to the ASTM C618 and EN 450-1 standards and determine its characteristics as a high or low calcium fly ash, [15], [16], [17].

To assess the temporal variability and stability of 1fly ash composition during the 2024–2025 monitoring period.

- To evaluate the mechanical performance of fly ash-containing cementitious systems through 7-day and 28-day compressive strength measurements.
- To investigate the relationships between chemical composition, physical properties, and compressive strength development using statistical and correlation analyses.
- To compare the chemical and mechanical characteristics of Kosovo B fly ash with lignite fly ashes reported in international literature and assess its industrial applicability, [18], [19].
- To evaluate the potential of Kosovo B fly ash as a clinker replacement material and its contribution to resource efficiency and sustainable cement production, [20], [21].
- To assess the environmental benefits associated with fly ash utilization, including waste valorisation, reduction of landfill disposal, conservation of natural raw materials, and support for circular economy strategies, [6], [7], [13].

2 Literature Review

Significant environmental, economic, and technical benefits can be noticed through the usage of fly ash as a supplementary cementitious material (SCM). Studies show that there is a refinement of pore structure, reduction of permeability, enhancement of durability and long-term improvement of mechanical properties of cement-based materials when fly ash partially replaces cement clinker, [22]. Furthermore, the incorporation of fly ash can reduce the consumption of natural raw materials and decrease the environmental footprint associated with cement production. An overview of the generation, characterization, and potential utilization of lignite fly ash from the Kosovo B Thermal Power Plant in cement production at Sharrcem is presented in Figure 1 (Appendix).

High-calcium (Class C) fly ash is particularly attractive due to its dual pozzolanic and hydraulic behaviour. Unlike low-calcium (Class F) fly ash, which primarily relies on reactions with calcium hydroxide released during cement hydration, Class C fly ash contains sufficient CaO to promote self-cementing reactions. Consequently, high-calcium fly ash can contribute to both early-age strength

development and long-term durability improvement, [23], [24]. There are several benefits tied to the partial replacement of clinker with fly ash, backed by research throughout the years. The performance of fly ash-based cementitious systems depends on many factors, among which are particle size distribution, mineralogical composition, amorphous phase content and chemical characteristics reported that the optimization of fly ash properties is essential for achieving sustainable cementitious materials with improved engineering performance [25] demonstrated that fly ash incorporation significantly affects the physical, mechanical, and microstructural characteristics of cement-based systems, highlighting the importance of material characterization and quality control.

In addition, demonstrated that the incorporation of fly ash not only reduces greenhouse gas emissions but also promotes the valorization of industrial by-products and decreases landfill disposal requirements.

However, maintaining consistent material properties remains a critical requirement for large-scale industrial implementation. Although extensive international research has investigated the application of fly ash in cementitious materials, limited information is available regarding the long-term chemical stability and mechanical performance of fly ash generated from the Kosovo B thermal power plant. Previous studies related to Kosovo lignite have mainly focused on combustion processes, operational optimization, and environmental monitoring, [1], [2]. Therefore, long-term monitoring of Kosovo B fly ash is necessary to establish its suitability as a sustainable supplementary cementitious material and to support its future industrial utilization.

3 Materials and Methods

3.1 Sampling Procedure

We collected representative fly ash samples monthly directly from the electrostatic precipitators at Kosovo B between January 2024 and December 2025. This yielded 24 distinct monthly samples, which were thoroughly homogenized and sealed to keep their properties intact for lab testing.

3.2 Technical Characterization of Fly Ash

The technical properties of fly ash were determined according to standard laboratory procedures. Among them, the moisture content (W) was determined by drying the samples at a temperature

of 105°C until a constant mass was achieved. Ash content (A) was determined by combustion at temperatures between 750°C and 815°C to quantify the inorganic residue. Whereas volatile matter (VM) was specified by heating the samples to a temperature of 900°C in an oxygen-free atmosphere for 7 minutes. Fixed carbon content (Cfix) was calculated using Equation (1):

$$C_{fix} = 100 - (W + A + VM) \quad (1)$$

where:

- W = moisture content (%)
- A = ash content (%)
- VM = volatile matter (%)

Loss on Ignition (LOI) was determined using standard fly ash testing procedures. Approximately 1 g of sample was heated at 950–1000°C to constant mass, and LOI was calculated as the percentage mass loss. The low unburned carbon content and efficient combustion conditions are the reasons for which the average LOI value was 2.88%.

3.3 Chemical Characterization by X-Ray Fluorescence (XRF)

When melted at high temperatures through the usage of VITRIX ELECTRIC apparatus, the finely ground samples blended with lithium borate flux create smooth glass beads. These beads were then analysed through XRF spectroscopy to identify target oxides. The major oxides in fly ash, due to the XRF analysis, have been found to be the following: SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , MgO , SO_3 , K_2O , and Na_2O . The analysis was done according to the highest standards, and instrument calibration was done according to laboratory quality-control procedures. The measurements were repeated to verify analytical precision and reproducibility. Table 1 provides a clear overview of the average chemical composition obtained during the time frame 2024–2025.

Table 1. Average chemical composition of Kosovo B fly ash (2024–2025)

Parameter	Average value (%)
LOI	2.88
SiO_2	32.28
Al_2O_3	9.01
Fe_2O_3	6.76
CaO	32.93
MgO	3.62
SO_3	11.42

Source: Created by the authors, Sharrcem Laboratory, Kosovo.

The analysis carried out indicates that the investigated fly ash belongs to the high-calcium category (Class C), as a result of the relatively high CaO content according to the ASTM C618 and EN 450-1 standards. The fact that such materials demonstrate both pozzolanic and self-cementing properties shows that they are adequate for cementitious applications.

3.4 Compressive Strength Evaluation

Two cast and cured blended cement samples showcase the following compressive capacities at two critical milestones:

- 7 Days: Averaged 14.66 MPa (ranging from 11.29 to 18.36 MPa).
- 28 Days: Averaged 35.14 MPa (ranging from 31.02 to 39.93 MPa).

3.5 Statistical Analysis

To understand consistency, we ran a Pearson correlation ($r = 0.82$, $p < 0.05$.) and descriptive summary on the full 24-month dataset.

Table 2. Summary statistics of fly ash properties

Parameter	Minimum	Maximum	Mean
S_iO_2 (%)	27.97	35.45	32.28
Al_2O_3 (%)	7.85	10.10	9.01
Fe_2O_3 (%)	6.06	7.76	6.76
CaO (%)	30.00	38.32	32.93
MgO (%)	1.89	5.17	3.62
SO_3 (%)	9.71	13.74	11.42
Moisture (%)	0.25	0.44	0.34
7-day strength (MPa)	11.29	18.36	14.66
28-day strength (MPa)	31.02	39.93	35.14

Source: Created by the authors, Sharrcem Laboratory, Kosovo.

3.6 Estimation of Environmental Benefits

The potential environmental benefits associated with clinker replacement were evaluated using literature-reported emission factors for Portland clinker production.

The reduction of carbon dioxide emissions was estimated according to:

$$CO_{2, reduction} = M_{clinker} \times EF_{clinker}$$

where:

- $M_{clinker}$ is the amount of clinker replaced by fly ash (t),

- $EF_{clinker}$ is the clinker emission factor (t CO_2 /t clinker).

Clinker production generates approximately 0.8–0.9 t CO_2 per ton of clinker. Therefore, partial substitution of clinker with fly ash contributes directly to reducing greenhouse gas emissions, further reinforcing the positive aspects a substitution of this kind has on the environment.

4 Conclusions

The chemical characterization of 24 fly ash samples collected from the Kosovo B thermal power plant during 2024–2025 showed average contents of 32.28% S_iO_2 , 9.01% Al_2O_3 , 6.76% Fe_2O_3 , and 32.93% CaO , with an average LOI of 2.88%. According to ASTM C618 requirements, the investigated material can be classified as high-calcium (Class C) fly ash, exhibiting both pozzolanic and self-cementing properties. Compressive strength values reached 14.66 MPa after 7 days and 35.14 MPa after 28 days. Statistical analysis indicated that moisture content negatively affected early-age strength development, while Al_2O_3 and Fe_2O_3 showed positive correlations with mechanical performance, emphasizing the importance of continuous quality contro.

The obtained results are consistent with findings reported for other high-calcium lignite fly ashes used in cementitious materials [21].[24]. Furthermore, the increase in fly ash consumption at the Sharrcem cement plant from 106,754.44 t in 2024 to 116,854.36 t in 2025 confirms its growing industrial acceptance. Kosovo B fly ash is therefore a suitable supplementary cementitious material for clinker replacement, contributing to resource conservation and reduced CO_2 emissions in cement production, [25].

5 Recommendations

Expand Industrial Utilization: The use of Kosovo B fly ash should be increased due to its demonstrated technical and environmental benefits in cementitious materials, [16], [17], [18], [19], [20], [21], [22], [23].

Implement Continuous Quality Control: Regular monitoring of moisture content and major oxide composition should be maintained to ensure compliance with ASTM C618 requirements and consistent product quality, [7].

Optimize Replacement Levels: Future studies should determine the optimum fly ash replacement ratio to maximize strength, durability, and environmental performance, [9], [12].

Strengthen Industry Collaboration: Cooperation between Kosovo B and the cement industry should be enhanced to ensure a stable fly ash supply and support circular economy practices [12], [25].

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Z. Bajraktari-Gashi: Conceptualization, research design, writing, and editing.

R. Berisha: Experimental work and data collection.

All authors reviewed and approved the final manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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APPENDIX

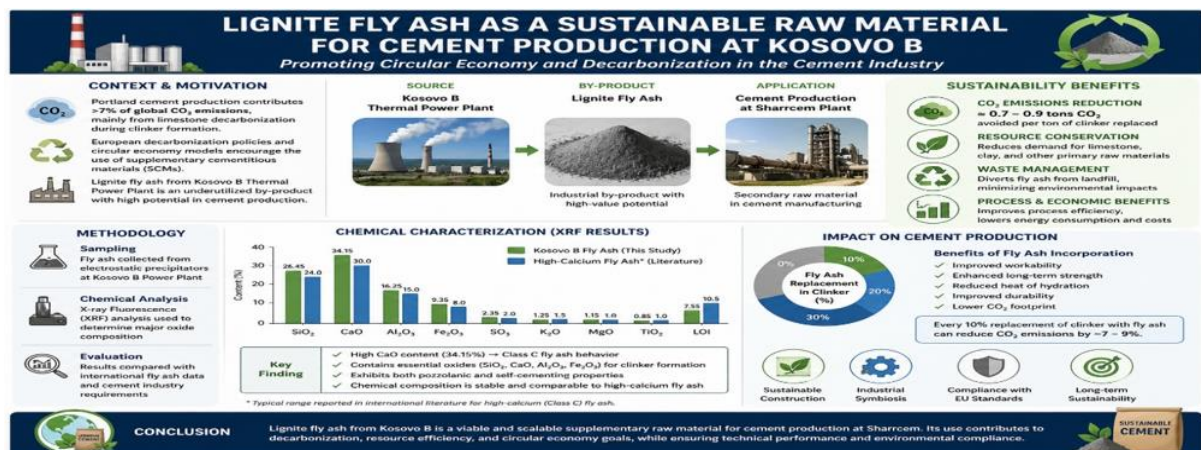


Fig. 1: Overview of lignite fly ash generation at Kosovo B, its XRF characterization, and potential utilization in cement production at Sharrcem.

Source: Created by the authors based on [1], [2], [19], and [25].