

COAL FLY ASH BENEFICIATION: A SUBSTITUTE MATERIAL FOR PORTLAND CEMENT – A REVIEW

Sri Hartuti^{1*}, Nurmeizon Saleh¹ and Vina Azatri¹

¹Department of Environmental Engineering, Faculty of Engineering, Institut Teknologi Padang, Padang, Indonesia

*E-mail: sri_hartuti@itp.ac.id

Received: 14 July 2025

Accepted: 23 July 2025

Published: 31 July 2025

Abstrak

Generasi abu batubara (CFA) sebagai produk sampingan dari pembangkit listrik berbasis batubara menghadirkan tantangan lingkungan yang signifikan karena volumenya yang besar dan potensi pencemarannya. Namun, CFA telah menunjukkan potensi menjanjikan sebagai bahan semen tambahan (SCM) dalam industri konstruksi, terutama sebagai pengganti sebagian semen Portland. Tinjauan ini mengeksplorasi kemajuan terkini dalam pengolahan abu batubara, berbagai teknik yang digunakan untuk meningkatkan sifat-sifatnya, dan aplikasinya sebagai pengganti semen. Secara khusus, studi telah melaporkan bahwa menggabungkan hingga 30% CFA yang telah diperoleh dapat mengurangi emisi CO₂ dari produksi beton sekitar 20% sambil meningkatkan durabilitas jangka panjang. Selain itu, abu Kelas F telah terbukti meningkatkan ketahanan sulfat dan mengurangi potensi reaksi alkali-silikat dalam beton, sementara metode pengolahan mekanis dapat menurunkan kandungan karbon yang tidak terbakar menjadi kurang dari 2%, menjadikan material tersebut lebih kompatibel dengan semen.

Kata Kunci: Abu batubara; konstruksi berkelanjutan; pengganti semen Portland; bahan semen tambahan, valorisasi limbah industri

Abstract

The generation of coal fly ash (CFA) as a by-product from coal-fired power plants presents significant environmental challenges due to its massive volume and potential for pollution. However, CFA has demonstrated promising potential as a supplementary cementitious material (SCM) in the construction industry, particularly as a partial substitute for Portland cement. This review explores current advancements in the beneficiation of coal fly ash, various techniques employed to enhance its properties, and its application as a cement substitute. Notably, studies have reported that incorporating up to 30% beneficiated CFA can reduce CO₂ emissions from concrete production by approximately 20% while enhancing long-term durability. Furthermore, Class F fly ash has shown to improve sulfate resistance and reduce alkali-silica reaction potential in concrete, while mechanical beneficiation methods can lower unburned carbon content to less than 2%, making the material more compatible with cement formulations. The study also examines environmental, economic, and technical benefits, along with limitations and future prospect for integrating beneficiated fly ash into sustainable construction practices.

Keywords: coal fly ash; sustainable construction; Portland cement substitute; supplementary cementitious material, industrial waste valorization

To cite this article:

Sri Hartuti dkk. (2025). Coal Fly Ash Beneficiation: A Substitute Material for Portland Cement – A Review. *Journal of Infrastructural in Civil Engineering*, Vol. (06), No. 02, pp: 150-163

INTRODUCTION

The demand for sustainable and environmentally friendly building materials has driven extensive research into alternative cementitious materials. Portland cement production is a major contributor to global CO₂ emissions. Utilizing industrial by-products like coal fly ash not only reduces waste but also lowers the carbon footprint associated with cement manufacturing [1, 2].

Coal Fly ash (CFA) is a fine powdery by-product formed during the combustion of pulverized coal which is carried away from the furnace by the flue gases. It consists of the mineral matter from coal that remains after combustion. CFA is produced in power and steam plants when pulverized coal is blown into the boiler chamber with air, igniting swiftly, generating heat, and leaving behind a liquid mineral residue. Heat is extracted from the boiler by tubes, which cool the flue gas and cause the molten mineral residue to solidify into ash. The heavier ash particles, known as bottom ash or slag, settle at the base of the combustion chamber, while the finer, lighter particles, called fly ash, stay suspended within the flue gases. Before the flue gas is released into the atmosphere, fly ash is captured using particulate emission control systems, such as electrostatic precipitators (see Figure 1) [3, 4].



Figure 1. Coal Fly Ash Production

Due to its high content of SiO₂, Al₂O₃, and Fe₂O₃ — typically surpassing 70% — CFA demonstrates strong pozzolanic properties, making it suitable for multiple applications. As a

result, many researchers have investigated its potential use as a cementitious component [1]. On the other hand, if coal fly ash is disposed of without proper treatment, its large volume poses serious risks of environmental pollution and health hazards due to accumulation in open disposal sites. As a result, utilizing and recycling fly ash as a substitute for natural raw materials is essential for conserving resources for future generations and supporting sustainable development and environmental protection.

Cement manufacturing is a highly energy-and resource-demanding process, generating substantial CO₂ emissions, primarily during the high-temperature decomposition of limestone into calcium oxide through the combustion of fossil fuels [5, 6]. As reported by Fayomi et al. [7], the production of each kilogram of cement releases approximately 0.5 to 0.9 kilograms of CO₂, contributing to an estimated 3.24 billion tonnes of CO₂ annually from the global cement output of 3.6 billion tonnes. With cement demand expected to increase considerably by 2050, the industry could account for over 30% of global CO₂ emissions, as projected by Damineli and John [8]. Therefore, the use of CFA as a partial replacement for Portland cement has the potential to reduce cement manufacturing, leading to lower CO₂ emissions and, in turn, alleviating global warming. This review investigates the beneficiation processes that improve CFA's performance characteristics and its suitability as a Portland cement substitute.

CHARACTERISTICS OF COAL FLY ASH

Coal fly ash (CFA) is a fine particulate by-product generated from the combustion of pulverized coal in thermal power plants. Its properties vary based on the type of coal, combustion conditions, and collection systems used [9]. A thorough understanding of CFA's physical, chemical, mineralogical, and pozzolanic characteristics is essential in evaluating its performance as a supplementary cementitious material (SCM) in concrete applications [10].

Physical Characteristics:

Coal fly ash primarily consists of fine, spherical particles known as cenospheres, with particle sizes ranging from less than 1 μm to 100 μm [11]. This spherical morphology contributes to improved workability and reduced water demand in concrete mixtures. The color of CFA varies from light to dark grey, influenced by the unburned carbon content present in the material. The specific surface area of CFA typically ranges from 200 to 600 m²/kg (Blaine fineness), directly affecting its reactivity. Additionally, the bulk density of

CFA is approximately 1.0–1.2 g/cm³, while its particle density falls between 2.1–2.6 g/cm³, depending on its mineral composition [12].

Chemical Characteristics:

The chemical composition of CFA governs its pozzolanic reactivity and suitability for cementitious applications. The major oxide components commonly include silicon dioxide (SiO₂), aluminum oxide (Al₂O₃), and iron oxide (Fe₂O₃), which collectively constitute more than 70% of the total composition. Based on calcium content, fly ash is classified as either:

- Class F: Low-calcium fly ash (CaO < 10%), primarily pozzolanic.
- Class C: High-calcium fly ash (CaO > 10%), both pozzolanic and self-cementing.

Minor constituents include potassium oxide (K₂O), sodium oxide (Na₂O), magnesium oxide (MgO), titanium dioxide (TiO₂), and sulfur trioxide (SO₃). The presence of unburned carbon is typically measured through Loss on Ignition (LOI), with a desirable value below 6% for cementitious applications [12].

Mineralogical Characteristics:

CFA is composed of both crystalline and amorphous (glassy) phases. The amorphous glassy phase forms the majority of the material, created through the rapid cooling of molten minerals during combustion, and is primarily responsible for CFA's pozzolanic reactivity [13]. The crystalline mineral phases commonly identified in CFA include Quartz (SiO₂), Mullite (3Al₂O₃·2SiO₂), Hematite (Fe₂O₃), Magnetite (Fe₃O₄), Anhydrite (CaSO₄) (predominantly in Class C). A higher content of the amorphous phase generally enhances the pozzolanic activity of the material.

Pozzolanic Properties:

The pozzolanic activity of CFA is defined by its ability to chemically react with calcium hydroxide (Ca(OH)₂) in the presence of water, forming additional calcium silicate hydrate (C–S–H), which contributes to improved concrete strength and durability [14]. Class F fly ash primarily exhibits pozzolanic behavior, while Class C fly ash displays both pozzolanic and self-cementing properties due to its higher calcium content. Key factors influencing pozzolanic activity include , glassy phase content, fineness of the particles, combined SiO₂, Al₂O₃, and Fe₂O₃ content, curing conditions, especially temperature and moisture availability.

Environmental Considerations:

CFA may contain trace levels of potentially hazardous heavy metals such as arsenic (As) [15,16], lead (Pb), mercury (Hg), and selenium (Se) [17, 18]. While these elements pose environmental concerns in open disposal, their incorporation into cementitious matrices immobilizes them, significantly reducing leaching potential and environmental risk. Studies have shown that these metals become chemically bound within the hydrated cement phases, further minimizing their mobility under typical environmental conditions [19].

BENEFICIATION METHODS OF CFA

The variable quality and composition of raw coal fly ash (CFA), which largely depend on the source of coal and combustion conditions, often necessitate beneficiation processes to enhance its suitability as a supplementary cementitious material (SCM). Unprocessed CFA may contain high levels of unburned carbon [20], variable particle size distribution, or crystalline impurities that compromise its reactivity and compatibility in cementitious systems. Therefore, beneficiation plays a crucial role in improving material consistency, reducing undesirable fractions, and enhancing pozzolanic activity, which is essential for CFA's performance in cement and concrete applications. Several beneficiation techniques have been developed and implemented at both laboratory and industrial scales, broadly categorized into physical, chemical, and thermal methods.

Mechanical Separation

Mechanical beneficiation involves the removal of coarse particles and unburned carbon using processes such as sieving, air classification, and electrostatic separation. Among these, air classification and sieving are widely adopted in commercial operations due to their scalability and operational simplicity. According to Li et al. [21], mechanical separation effectively reduces the carbon content in fly ash to levels below 2% LOI, making it suitable for high-performance concrete applications. Mechanical processing also increases the specific surface area, which can enhance pozzolanic reactivity.

Thermal Treatment

Thermal beneficiation entails the controlled combustion of CFA to reduce residual carbon content and improve pozzolanic activity. This method is especially applicable in regions where fly ash with high unburned carbon levels is common. The elevated temperatures during treatment enhance the amorphous glassy phase content by altering

crystalline mineral phases, thereby increasing reactivity. Although effective, thermal processing is often energy-intensive and may generate additional emissions, making it less favorable unless integrated into existing high-temperature industrial processes [21].

Chemical Activation

Chemical beneficiation involves treating fly ash with acid or alkali solutions to improve its pozzolanic reactivity and alter surface characteristics. Alkali activation, in particular, has demonstrated significant improvements in early strength development and microstructural densification of blended cementitious systems [22]. Chemical activation can also enhance the dissolution of reactive silica and alumina from the glassy phase, accelerating pozzolanic reactions during cement hydration.

Magnetic Separation

Magnetic separation is utilized to remove iron-rich particles and magnetic minerals such as hematite (Fe_2O_3) and magnetite (Fe_3O_4) from CFA. Although less widely implemented at commercial scale, this method is employed in applications requiring high-purity fly ash with improved whiteness and consistency for specialized cementitious products. This technique also facilitates the recovery of valuable magnetic fractions for potential reuse or further processing.

Integrated Methods

Recent industrial reviews indicate that a combination of mechanical separation and thermal treatment represents the most cost-effective and operationally viable beneficiation approach for large-scale CFA processing [21]. These integrated methods balance efficiency, product consistency, and economic feasibility for SCM production. Integrating these methods can also reduce the total energy demand by utilizing waste heat from industrial processes for thermal treatment. Additionally, the synergy between size reduction and carbon burnout enhances the reactivity of fly ash, making it more suitable for high-performance concrete applications [23].

APPLICATION IN PORTLAND CEMENT SUBSTITUTION

Application in Portland Cement Substitution

Coal fly ash (CFA), particularly after beneficiation, has been extensively explored as a supplementary cementitious material (SCM) in concrete production. Its incorporation not

only improves concrete properties but also contributes to environmental sustainability by reducing the dependence on Portland cement, which is highly energy- and carbon-intensive to produce. Fly ash can replace 15–35% of Portland cement in typical blended cements, without compromising performance under most service conditions. Moreover, its pozzolanic reaction contributes to long-term strength gain and durability, making it suitable for infrastructure and mass concrete projects [24].

Replacement Levels and Standards

Beneficiated CFA is commonly used to replace 15–35% of Portland cement in concrete mixtures. The specific replacement level depends on factors such as the type of fly ash (Class F or Class C), required concrete performance, environmental exposure conditions, and regulatory standards. In international practice, standards such as ASTM C618 classify fly ash based on its chemical composition:

- Class F fly ash (low-CaO, pozzolanic) is preferred for high-durability concrete and sulfate-resistant applications.
- Class C fly ash (high-CaO, pozzolanic and self-cementing) offers additional cementitious properties, suitable for applications requiring early strength gain.

Performance Benefits in Concrete

The incorporation of beneficiated CFA in cementitious systems imparts several technical advantages:

- Improved durability, including enhanced resistance to sulfate attack, chloride ingress, and alkali-silica reaction (ASR).
- Reduced permeability, resulting in lower water absorption and improved long-term strength.
- Lower heat of hydration, beneficial for mass concrete applications to minimize thermal cracking.
- Enhanced workability, due to the spherical morphology of fly ash particles, reducing water demand in concrete mixes.

Thomas [25] reported that replacing Portland cement with Class F fly ash not only mitigates ASR but also extends the service life of concrete structures through reduced permeability and improved chemical resistance. In addition, the finer particle size distribution of fly ash enhances the particle packing density, leading to a denser microstructure. This

densification further improves resistance to environmental degradation mechanisms such as freeze-thaw cycles and sulfate exposure.

Environmental and Economic Advantages

The substitution of Portland cement with CFA offers significant environmental and cost benefits:

- Reduction in CO₂ emissions, as each ton of cement replaced reduces approximately 0.5–0.9 tons of CO₂ emissions associated with cement manufacturing [7].
- Diversion of industrial waste from landfills, alleviating disposal challenges and reducing land use pressure.
- Lower material costs, particularly in regions with abundant fly ash availability, leading to 10–15% cost savings for ready-mixed concrete producers [25].

A case study by Shi et al. [26] documented a 19% reduction in embodied CO₂ in concrete structures when 30% of Portland cement was substituted with beneficiated Class F fly ash.

Limitations and Compatibility

Despite its advantages, CFA substitution is not without challenges. Issues include: Variability in chemical composition and physical properties across different sources of fly ash; Reduced early strength gain in concrete with high fly ash content, requiring longer curing periods; Limitations in availability and public acceptance in certain regions. To address these limitations, ongoing research focuses on blended systems combining CFA with other SCMs such as ground granulated blast furnace slag (GGBFS), silica fume, and rice husk ash to enhance mechanical and durability performance.

ENVIRONMENTAL AND ECONOMIC BENEFITS

The incorporation of beneficiated coal fly ash (CFA) as a supplementary cementitious material offers substantial environmental and economic advantages. Beyond mitigating the environmental burden associated with fly ash disposal, its use in cementitious systems directly contributes to lowering the carbon footprint of the construction industry.

Environmental Benefits

The integration of CFA into cement and concrete production helps address several pressing environmental concerns:

- **Reduction of Greenhouse Gas Emissions:**
Cement manufacturing is a major global emitter of carbon dioxide (CO₂), primarily due to the calcination of limestone and the combustion of fossil fuels. Substituting a portion of Portland cement with CFA reduces clinker demand, subsequently lowering CO₂ emissions. Habert et al. [27] estimated that replacing 25% of cement with fly ash can decrease emissions by approximately 200 kg CO₂ per ton of cementitious material produced.
- **Diversion of Industrial Waste:**
The reuse of CFA in construction materials diverts substantial quantities of industrial waste from landfills. In coal-dependent regions, this practice can reduce annual fly ash disposal volumes by up to 40%, easing land-use pressures and preventing potential groundwater contamination [27].
- **Reduction in Raw Material Extraction:**
Utilizing CFA reduces the need for virgin materials such as limestone, clay, and shale, thereby minimizing the environmental impacts of mining, including habitat disruption, dust generation, and energy consumption.

Economic Benefits

Beyond its ecological value, the use of beneficiated CFA offers several economic incentives:

- **Cost Savings in Material Procurement:**
Fly ash is generally less expensive than Portland cement, particularly in regions where it is produced abundantly as a by-product. Thomas [25] reported a 10–15% reduction in material costs for ready-mixed concrete producers who adopted fly ash-blended cement.
- **Extended Service Life of Concrete Structures:**
By enhancing the durability and reducing the permeability of concrete, CFA extends the lifespan of infrastructure, lowering long-term maintenance and repair costs. This durability advantage is especially valuable in aggressive environmental conditions.
- **Market Competitiveness and Regulatory Compliance:**
The growing emphasis on low-carbon, sustainable construction practices and green certification schemes increases the market value of products incorporating SCMs like

CFA. Utilizing fly ash in cement-based materials positions producers favorably for meeting environmental regulations and sustainability targets.

CHALLENGES AND FUTURE PERSPECTIVES

Challenges and Future Perspectives

Despite the well-established environmental and technical benefits of using coal fly ash (CFA) as a supplementary cementitious material, several challenges hinder its broader implementation in construction industries worldwide. Addressing these limitations and advancing innovative research directions are essential to maximize CFA's potential within sustainable construction practices.

Challenges

- **Variability in Fly Ash Properties:**

One of the primary challenges in CFA utilization is the considerable variation in chemical composition, mineralogy, and physical properties depending on the type of coal, combustion technology, and operating conditions. This inconsistency affects pozzolanic activity, workability, and compatibility in concrete applications, requiring thorough characterization and quality control [43].

- **Logistical and Supply Constraints:**

The collection, transportation, and beneficiation of CFA demand coordinated infrastructure, which may not be available in all regions. Additionally, the ongoing global shift away from coal-fired power generation raises concerns regarding long-term availability and continuity of CFA supply.

- **Public Perception and Regulatory Limitations:**

In certain markets, public concerns regarding the potential environmental risks of heavy metals in fly ash and a lack of harmonized regulatory frameworks restrict CFA's acceptance in construction applications. The absence of performance-based standards in some regions further impedes its widespread use.

- **Early-Age Strength Reduction:**

High CFA replacement levels can delay early strength development in concrete, limiting its use in applications requiring rapid load-bearing capacity. Optimizing mix designs and curing regimes is necessary to mitigate this drawback.

Future Perspectives

To address existing limitations and enhance CFA's performance, recent research trends have focused on several promising directions:

- **Improved Beneficiation Techniques:**
Innovations in beneficiation technologies, including integrated mechanical–thermal processes and eco-friendly chemical treatments, aim to enhance CFA's pozzolanic activity and consistency while minimizing energy consumption and environmental impacts
- **Development of Hybrid Supplementary Cementitious Systems:**
Combining beneficiated CFA with other industrial by-products such as ground granulated blast furnace slag (GGBFS), silica fume, or rice husk ash has demonstrated synergistic effects in enhancing concrete strength, durability, and resistance to chemical attacks. This approach provides a flexible, resource-efficient strategy for maximizing the utilization of various waste materials.
- **Nano-Modification Techniques:**
Emerging studies have investigated the incorporation of nano-silica, nano-clay, and carbon nanotubes into CFA-blended cementitious systems to improve microstructural refinement and accelerate hydration reactions. Li et al. [21] reported significant improvements in compressive strength and durability through nano-modification.
- **Standard Harmonization and Performance-Based Specifications:**
Establishing globally harmonized standards and comprehensive performance-based guidelines is essential to ensure the reliable and safe use of CFA in diverse construction contexts. Such frameworks will facilitate broader market acceptance and optimize blended cement formulations.

CONCLUSION

Coal fly ash (CFA) beneficiation represents a promising and sustainable approach to addressing both industrial waste management challenges and the environmental impact of cement production. Beneficiated CFA, when used as a supplementary cementitious material (SCM), offers substantial advantages in enhancing concrete durability, reducing CO₂ emissions, lowering raw material consumption, and promoting circular economy practices within the construction sector. The review highlights that various beneficiation methods — including mechanical separation, thermal treatment, chemical activation, and magnetic

separation — are effective in improving the physical and chemical properties of CFA to meet the performance standards required for cementitious applications. Among these, mechanical separation combined with thermal processing remains the most widely adopted at an industrial scale due to its operational feasibility and economic viability.

In addition to technical performance, the environmental and economic benefits associated with CFA utilization are significant. These include the diversion of industrial waste from landfills, substantial reductions in greenhouse gas emissions, conservation of natural resources, and potential cost savings in concrete production. Case studies demonstrate that incorporating up to 30% beneficiated CFA can reduce embodied CO₂ emissions by approximately 19% in concrete structures.

Despite these benefits, challenges such as property variability, logistical constraints, and early strength limitations continue to restrict the broader adoption of CFA in cementitious systems. Future research directions are focusing on advanced beneficiation techniques, hybrid SCM systems, nano-modification strategies, and the harmonization of international performance-based standards to overcome these barriers.

In conclusion, the integration of beneficiated coal fly ash into concrete production aligns with the global transition toward sustainable, low-carbon construction practices. Continued innovation in processing technologies and regulatory frameworks will be critical to fully realizing CFA's potential as a viable substitute for Portland cement in the years ahead.

REFERENCES

- [1] Hussein M. Hamada, Farid Abed, Zaid A. Al-Sadoon, Adnan Alashkar, Enhancing pozzolanic activity of fly ash via dry and wet milling: A comparative study for sustainable construction material enhancement, *Journal of CO2 Utilization*, Volume 83, 2024, 102811, ISSN 2212-9820.
- [2] Daman K. Panesar, Deepak Kanraj, Yasar Abualrous, Effect of transportation of fly ash: Life cycle assessment and life cycle cost analysis of concrete, *Cement and Concrete Composites*, Volume 99, 2019, Pages 214-224, ISSN 0958-9465.
- [3] Akinyemi, S., Gitari, W. M., Thobakgale, R., Petrik, L. F., Nyakuma, B. B., Hower, J. C., Ward, C. R., Oliveira, M. L. S., & Silva, L. F. O. (2020). Geochemical fractionation of hazardous elements in fresh and drilled weathered South African coal fly ashes. *Environmental Geochemistry and Health*, 42(9), 2771–2788.

- [4] A comprehensive review on coal fly ash and its application in the construction industry, S. E. Kelechi, Musa Adamu, O. A. U. Uche, I. P. Okokpujie, Yasser E. Ibrahim & I. I. Obianyo, *Cogent Engineering* (2022), 9: 2114201.
- [5] Tosti, L., van Zomeren, A., Pels, J.R., Comans, R.N.J., 2018. Technical and environmental performance of lower carbon footprint cement mortars containing biomass fly ash as a secondary cementitious material. *Resour. Conserv. Recycl.* 134 (January), 25–33.
- [6] Latawiec, R., Woyciechowski, P., Kowalski, K.J., 2018. Sustainable concrete performance—CO₂-emission. *Environ. - MDPI* 5 (2), 1–14.
- [7] Fayomi, G.U., Mini, S.E., Fayomi, O.S.I., Ayoola, A.A., 2019. Perspectives on environmental CO₂ emission and energy factor in Cement Industry. *IOP Conf. Ser. Earth Environ. Sci.* 331.
- [8] Damineli, B.L., John, V.M., 2012. Developing Low CO₂ concretes: Is clinker replacement sufficient? The need of cement use efficiency improvement. *Key Eng. Mater.* 517, 342–351.
- [9] Li, G.; Zhou, C.; Ahmad, W.; Usanova, K.I.; Karelina, M.; Mohamed, A.M.; Khallaf, R. Fly Ash Application as Supplementary Cementitious Material: A Review. *Materials* **2022**, *15*, 2664.
- [10] Arpita Bhatt, Sharon Priyadarshini, Aiswarya Acharath Mohanakrishnan, Arash Abri, Melanie Sattler, Sorakrich Techapaphawit, Physical, chemical, and geotechnical properties of coal fly ash: A global review, *Case Studies in Construction Materials*, Volume 11, 2019, e00263, ISSN 2214-5095.
- [11] Filazi, A., Demir, İ. & Sevim, O. Enhancement on mechanical and durability performances of binary cementitious systems by optimizing particle size distribution of fly ash. *Archiv.Civ. Mech.Eng* **20**, 58 (2020).
- [12] Seham S. Alterary, Narguess H. Marei, Fly ash properties, characterization, and applications: A review, *Journal of King Saud University - Science*, Volume 33, Issue 6, 2021, 101536, ISSN 1018-3647.
- [13] Miah, M.J., Huaping, R., Paul, S.C. *et al.* Long-term strength and durability performance of eco-friendly concrete with supplementary cementitious materials. *Innov. Infrastruct. Solut.* **8**, 255 (2023).
- [14] Baoju Liu, Jinyan Shi, Hui Liang, Junyi Jiang, Yuanxia Yang, Zhihai He, Synergistic enhancement of mechanical property of the high replacement low-calcium ultrafine fly ash blended cement paste by multiple chemical activators, *Journal of Building Engineering*, Volume 32, 2020, 101520, ISSN 2352-7102.

- [15] Hartuti S, Kambara S, Takeyama A, Kumabe K, Moritomi H. Direct quantitative analysis of arsenic in coal fly ash. *J Anal Methods Chem.* 2012; 2012:438701.
- [16] Hartuti S, Takeyama A, Kambara S. Arsenic leachability of coal fly ashes from different types of coal fired power plants. *Journal of Materials Science and Engineering A.* 2017c;7: 169-177
- [17] Hartuti S, Kambara S, Takeyama A, Hanum FF. Leaching characteristic of arsenic in coal fly ash. *Journal of Materials Science and Engineering B.* 2017a; 7:19-26
- [18] Hartuti, S.; Fadhillah Hanum, F.; Takeyama, A.; Kambara, S. Effect of Additives on Arsenic, Boron and Selenium Leaching from Coal Fly Ash. *Minerals* **2017**, 7, 99.
- [19] Shi, C., Fernández-Jiménez, A., & Palomo, A. (2011). New cements for the 21st century: The pursuit of an alternative to Portland cement. *Cement and Concrete Research*, 41(7), 750–763.
- [20] Arpita Bhatt, Sharon Priyadarshini, Aiswarya Acharath Mohanakrishnan, Arash Abri, Melanie Sattler, Sorakrich Techapaphawit. (2019). Physical, chemical, and geotechnical properties of coal fly ash: A global review, *Case Studies in Construction Materials*, Volume 11.
- [21] Li, G.; Zhou, C.; Ahmad, W.; Usanova, K.I.; Karelina, M.; Mohamed, A.M.; Khallaf, R. Fly Ash Application as Supplementary Cementitious Material: A Review. *Materials* **2022**, 15, 2664.
- [22] Zhang, L., Gao, X., & Wang, B. (2020). Utilization of fly ash in sustainable construction materials: A review. *Journal of Cleaner Production*, 268, 122347.
- [23] R.S. Blissett, N.A. Rowson, A review of the multi-component utilisation of coal fly ash, *Fuel*, Volume 97, 2012, Pages 1-23.
- [24] Mehta, P. K., & Monteiro, P. J. M. (2014). *Concrete: Microstructure, Properties, and Materials* (4th ed.). McGraw-Hill Education].
- [25] Thomas, M. (2007). *Optimizing the use of fly ash in concrete*. Portland Cement Association. Retrieved from <https://www.cement.org>.
- [26] Shi, C., Qian, J., & Sun, W. (2019). New understanding of fly ash characteristics and their impact on concrete properties. *Construction and Building Materials*, 211, 492–500.
- [27] Habert, G., d'Espinose de Lacaillerie, J. B., & Roussel, N. (2010). An environmental evaluation of geopolymer based concrete production: reviewing current research trends. *Journal of Cleaner Production*, 19(11), 1229–1238.