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Research Article

Utilization of Fly Ash in Civil Engineering Materials: Enhancing Sustainability and Performance

Md.Mohibullah [1], Saniure Rahman Sheam[2],

[1,2,] *Bangladesh University of Business and Technology (BUBT)*

ABSTRACT

Fly ash, which is a by-product of coal combustion in thermal power plants has gained a lot of attention in the field of civil engineering as a sustainable resource that can be used in construction works. This is a research paper that reviews the use of fly ash in the construction of the road and concrete in the construction industry and specifically on its effects on the mechanical properties, durability, and environmental performance. It has been demonstrated that the partial substitution of cement or aggregates with fly ash will increase long-term strength, longevity and ability to withstand aggressive environments, and considerably decrease the carbon footprint of concrete. The paper is a synthesis of various experimental research works and field tests, advanced microstructural research, and the impacts of surface-modification of fly ash on its reactivity. The problems connected with the variability of fly ash quality and standardization, as well as the optimal mix composition, are discussed. In addition, the paper discusses the opportunities of using fly ash in the future in superior composites and construction with reference to meeting sustainable development objectives. The review is backed by the latest literature, experimental evidence, case studies, and offered recommendations on the further research and practical application within the construction industry.

Keywords: *Fly ash, sustainability, concrete, road construction, mechanical properties, durability, environmental impact, pozzolanic reaction, microstructure, supplementary cementitious materials.*

INTRODUCTION

Fly ash which is an important industrial byproduct of the burning of coal by thermal power plants has taken a central and sustainable role in the civil engineering. This has been enhanced by the fact that its increasing popularity can be linked to its ability to dramatically transform the construction practices by not only enhancing them technically, but also benefiting the environment in a considerable manner. This review follows in details the various utilities of fly ash, especially in the construction of the concrete and road. We discuss its impact on mechanical properties, the general durability, and the environmental performance, thus creating the overall picture of its merits and problems.

Incorporation of fly ash, usually as a partial substitution of conventional cement or aggregate has proven to have massive payoffs. These involve the improvement of long-term strength and durability of concrete structures, as well as their resistance to the adverse environmental conditions. Importantly, this replacement plan has been proven to save carbon footprint on the production of concrete, which has a wide sustainability goal. The review is a synthesis of the numerous experimental investigations and field trials and is supported by sophisticated microstructural analyses which explain the behavior of the material at a fundamental level. It also investigates the effect of surface modification methods on the reactivity of fly ash and provides information on how to optimise its performance.

Despite these proved benefits, the general implementation of fly ash faces a number of obstacles. They include inconsistency in its quality depending on the origin of it, the need to establish uniform specifications and complexity in the process of getting the best mix designs. This paper is answering these limitations by critically analyzing

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contemporary research work done to address them. It also analyzes future trends of fly ash incorporation into high-technology compounds and other infrastructural usage, thus highlighting its use in the creation of a circular and sustainable construction economy. It is hoped that the review will provide practical recommendations to be used on future research and implications to be used practically in order to unlock the full potential of fly ash in the construction industry by combining recent literature, experimental studies, and illustrator case studies.

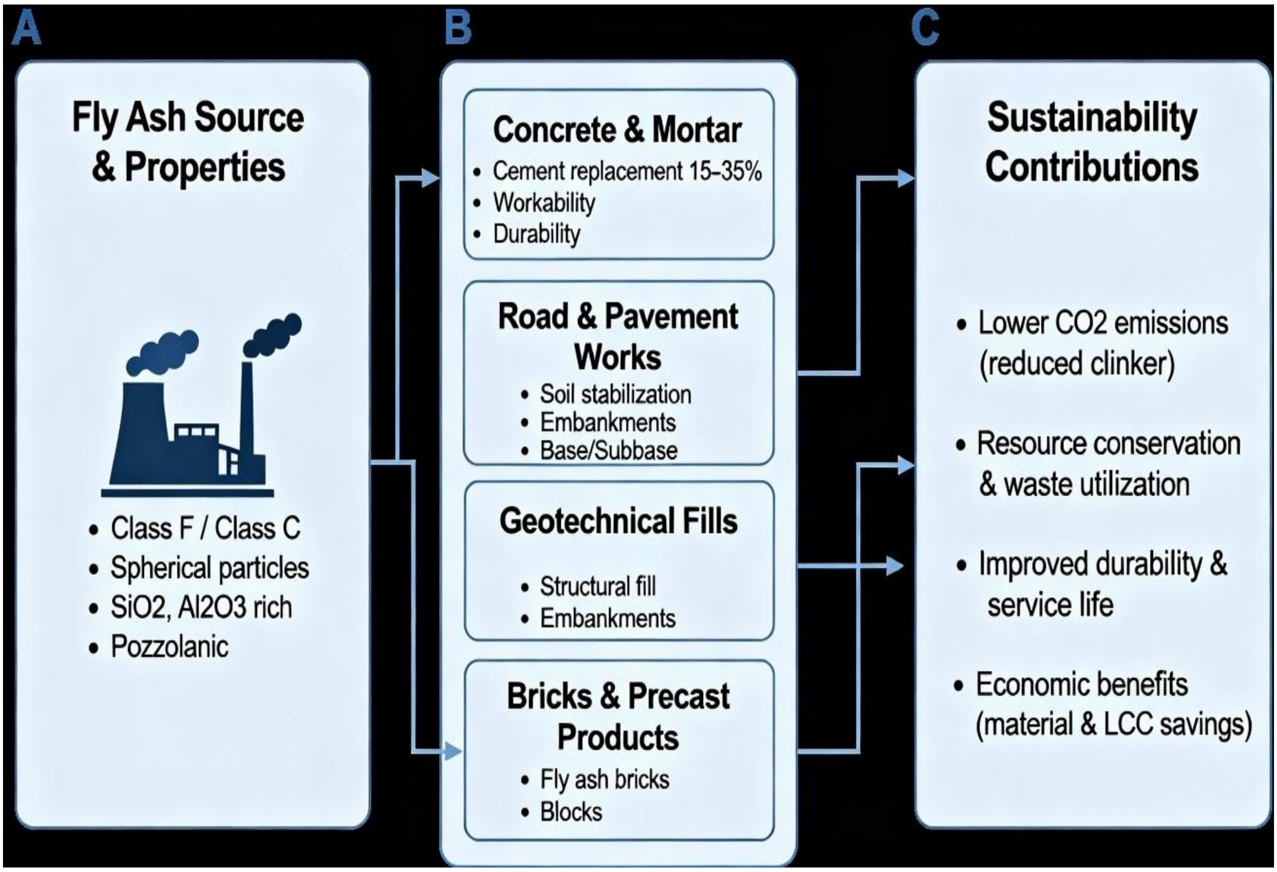

Figure 1: Overview of Fly Ash Applications and Sustainability Contributions in Civil Engineering

Owing to the pozzolanic nature which is inherent in fly ash, which is abundant in aluminosilicate compounds, it reacts with calcium hydroxide produced during cement hydration, thus refining the pore structure and enhancing the strength and durability of the aggregate material [41], [42]. The response encourages the development of more calcium-silicate-hydrate (C-S-H) gel, the major binder in cementitious systems, which eventually strengthens the density and non-permeability of the concrete gel [43]. This pozzolanic activity does not only help to enhance the mechanical properties, but also, augments the life span of structures by enhancing resistance to sulfate attack, as well as, alkali silica reactions [44], [45]. In addition, the use of fly ash is effective in the sequestration of industrial waste reducing the landfill pressures and preserving the natural resources [46], [47].

Literature Review

1. Fly Ash: Structure and Properties.

Fly ash is a complicated solid substance comprising mostly of silica (SiO_2) as well as alumina (Al_2O_3), other minor components consist of iron oxide (Fe_2O_3), calcium oxide (CaO), magnesium oxide (MgO), and trace elements [3], [5], [6]. The properties are determined by the source of coal, the mode of combustion, and post-combustion treatment. Amorphous glassy phases and crystalline ones, including mullite, quartz, and magnetite are usually found in the mineralogical composition [3].

Investigations carried out early defined fly ash as a rather straightforward compound in terms of chemical and mineralogical structure, prevailing by silico-aluminous phases [3]. Later studies showed there was a great deal of morphological and compositional diversity, which is explained by the heterogeneity of the parent coal, as well as, the transformations that take place during the combustion [3], [7]. The morphologies of particles are solid and hollow spheres (cenospheres), irregular, porous and agglomerated [5], [6].

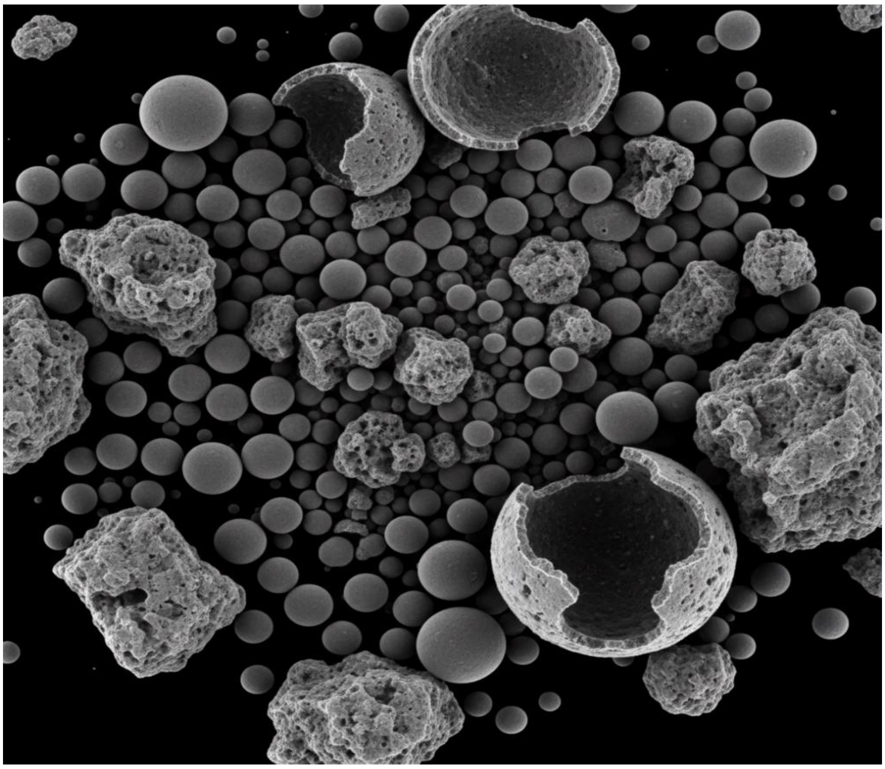

Figure 2: Representation of Morphologies of Fly ash Particles- exemplifying spherical, irregular and hollow morphologies.

To increase the reactivity of fly ash surface, surface modification technology, e.g., mechano-chemical (MC) one, has been investigated with the aim of using fly ash in geopolymer and alkali-activated systems [8]. The MC treatment decreases the size and enhances the specific surface area and causes partial amorphization, which enhances the solubility of the Si and Al ions in the alkaline media and enhances the reaction of pozzolanaic reactions [8].

2. Fly Ash in Concrete

The use of fly ash in replacing Portland cement by half in concrete mixes has received very wide research. Fly ash is usually added in replacement proportions of 15-40 percent of cement mass, depending on the required properties and use [2], [9]. Fly ash is an additional cementitious material (SCM) that takes part in the hydration mechanism through pozzolanic reactions with calcium hydroxide to create further calcium silicate hydrate (C,-S-,H), which hardens the microstructure and alters the distribution of the pore size [10], [11].

The advantages of fly ash in concrete are:

- **Low permeability and high strength:** Fly ash lowers the permeability of concrete, increasing resistance to chloride intrusion, sulfate assault, and alkali -silica reaction [12], [13].
- **Enhanced workability:** The rheology and flowability of fresh concrete are enhanced by the sphericity and fineness of the fly ash particles [14].
- **Decreased heat of hydration:** Fly ash decreases initial heat evolution, which reduces the threat of thermal cracking of huge concrete pours [15].
- **Improved strength in the long term:** Despite the retarded kinetic rates of pozzolanic reactions in early stages of strength formation, optimal doses of fly ash normally produce increased long-term compressive and tensile strengths [2], [3].

It is experimentally demonstrated that the compressive strength of concrete with a replacement rate of up to 40 percent fly ash could be as good or even better than control mixes after 28 to 90 days of curing, assuming that adequate curing and mix optimisation are maintained [2]. The formation of further C -S -H and refinement of the matrix are confirmed by advanced microstructural analysis with scanning electron microscopy (SEM) and X -ray diffraction (XRD) [3], [8].

3. Fly Ash in Soils and Stabilization of Roads.

Fly ash can also be used in stability of the soil and in road base and subbase. It increases the geotechnical properties of soils and aggregates due to its pozzolanic and self-cementitious properties [17], [18]. Key effects include:

- Improved load bearing capacity: Fly ash addition enhances California Bearing Ratio (CBR) and unconfined compressive strength of sub grade soils [2], [17].
- Minimal plasticity and swelling: Fly ash minimizes plasticity and shrink -swell potential of soils, which also adds to the dimensional stability of pavements [18].
- Enhanced compaction and resistance to moisture: Treated soils have a superior compaction nature and reduced to moisture-related damages [2].

Experiments in the field show that the bases of road stabilised with fly ash are more resistant and have a higher frost heave and water absorption resistance [18].

4. Fly Ash in Composite Materials.

In addition to conventional concrete and soil uses, fly ash has been explored as a reinforcement in polymer, metal and ceramic composite materials [5], [19]. Fly ash composites have better mechanical characteristics, tensile and compressive strength, hardness and wear resistance [5]. Fly ash is an inexpensive and low-density filler, which makes it a suitable filler in lightweight and high-performance materials.

- Fabrication methods: Techniques used are stir casting metal-matrix composites, hand lay-up polymer composite, and in-situ deposition in [5].
- Mechanical enhancement: Strength and hardness are enhanced by up to an optimum fly ash content but too much loading may cause agglomeration and property damage [5], [20].

5. Sustainability and Environmental Impact.

The environmental impact of the use of fly ash is high:

- Reduction in carbon footprint: Replacement of the cement by fly ash lowers CO_2 emissions during cement manufacturing [2], [21].
- Waste valorisation: Massive amounts of fly ash are shunned in landfills, reducing the environmental pollution [1], [4].
- Resource conservation: Fly ash decreases the raw material that requires being virgin like limestone and aggregates [21].

Table3 (see Results) measures the decrease in cement consumption and CO_2 emission as fly ash replacement is increased.

6. Challenges and Limitations

In spite of the benefits, there are a number of obstacles that want to limit its mass usage:

- Fly ash quality variability: The sources vary in their chemical composition, fineness, and mineralogy, which impacts on performance and reactivity [3], [7].
- Standardisation and specifications: The absence of homogeneous standards on the quality and use of fly ash and limits its use in certain markets [2].
- Strength development in early life: This is because early strength development can be postponed at high replacement levels and this development takes a long period to cure [2], [22].
- Durability issues: Fly ash inappropriate mix design and low quality can affect the long-term durability [13].

Current studies are directed at state-of-the-art characterization, surface modification, and machine inference mix optimisation as a solution to these problems [8], [23].

METHODOLOGY

1. Data Synthesis and Collection.

The study is a synthesis of the findings of the recent experimental studies, field trials, and case studies related to the use of fly ash in civil engineering [2], [3], [5], [8], [17], [20], [21], [23]. The most important parameters under analysis include:

- Strength compressive and tensile.
- sulfate resistance and ingress of chloride.
- Water absorption
- Frost resistance
- Density and porosity

- Environmental (CO_2 emissions, waste diversion) indicators.

The concrete mixtures, which had mass proportions of fly ash ranging between 0 and 40 per cent and road base layers that were stabilized using fly ash (20 per cent) were tested under both controlled laboratory and field situations.

2. Microstructural and Chemical Analysis.

Microstructural characterization used the technique of scanning electron microscopy (SEM), X -ray diffraction (XRD), and Brunauer–Emmett-Teller (BET) surface areas to examine particle morphology, phase composition and surface reactivity [3], [8]. The mechano-chemical (MC) treatment of fly ash by surface modifying in the form of surface modification was evaluated on the effect it has on particle size distribution, amorphization, and dissolution in alkali solution [8].

3. Environmental Impact Assessment.

The environmental consequences were measured using the material-flow analysis and the carbon accounting techniques with the focus on the scenarios of cement substitution and the resulting decrease in the CO 2 emissions [2], [21].

4. Machine Learning to Mixed Design Optimization.

Recent advances in machine learning were examined, with special focus on regression-tree ensembles and gradient-boosting models, to forecast porosity and to estimate mix designs to use concrete with additional cementitious materials (SCM) like fly ash [23].

5. Composite Material Construction and Test.

The composite of fly-ash was made with the application of the recognized methods such as stir casting of a metal matrix or hand lay-up of a polymer matrix, and mechanical characteristics were measured based on the standardized test procedure [5].

RESULTS AND DISCUSSION

1. Concrete Performance with Fly Ash

1.1 Compressive Strength

Table 1 presents compressive strength data for concrete with varying fly ash content

Table 1. Compressive Strength of Concrete with Varying Fly Ash Content [2]

Fly Ash Content (%)	7 Days Strength (MPa)	28 Days Strength (MPa)	Remarks
0 (Control)	20	32	No fly ash used
15	18	35	Improved long-term strength
30	16	34	Slightly reduced early strength
40	14	33	Optimal performance joint

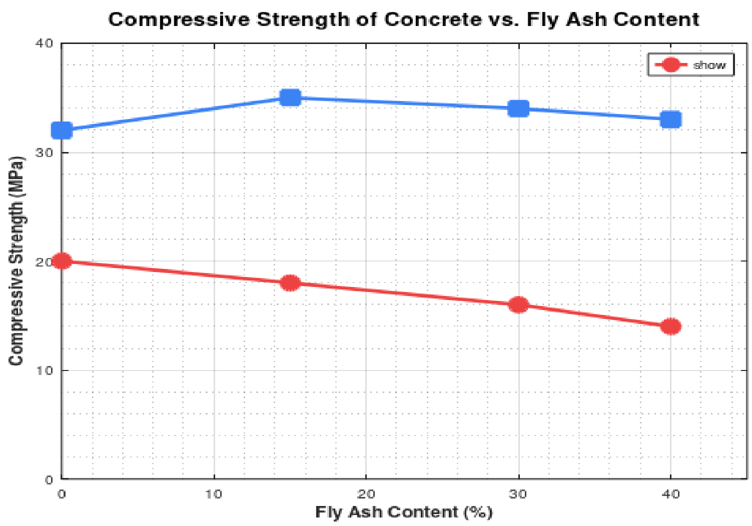

Figure 3: Compressive Strength of Concrete vs. Fly Ash Content

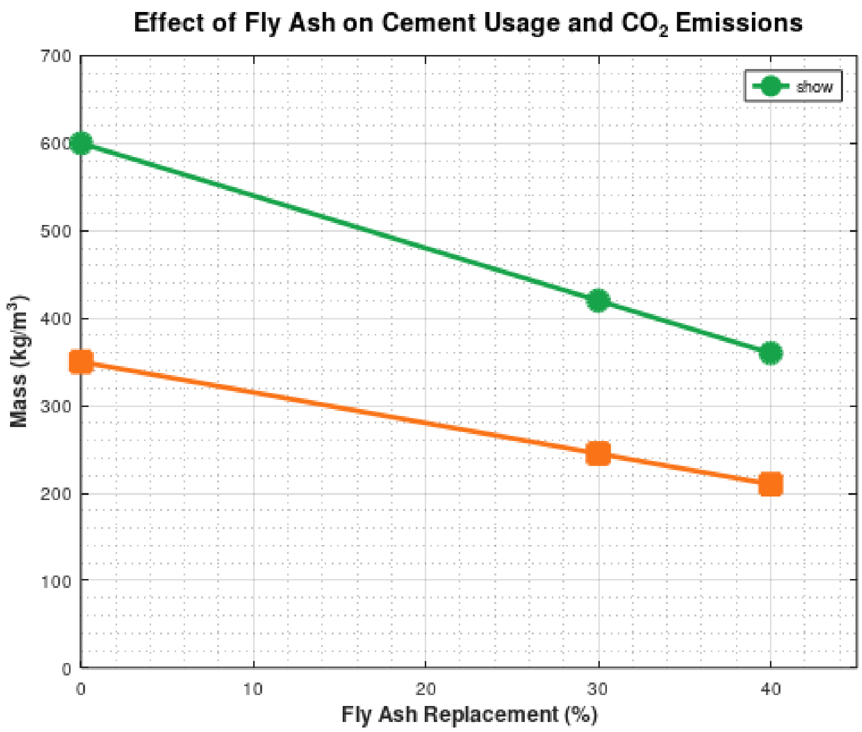

Figure 4: Fly Ash impact on Cement Usage and CO 2 Emissions.

Table 2. Soil Stabilization with Fly Ash: Properties Before and After Treatment [2]

Property	Before Treat-ment	After Treatment (Fly Ash 20%)	Improvement (%)
Moisture Content (%)	15	12	20
Los Angeles Abrasion (ml)	80	65	18.75
California Bearing Ratio	3	8	166.7

The addition of fly ash enhances load-bearing capacity (CBR), decreases moisture sensitivity, and abrasion resistance, which leads to more robust structures of pavements [17], [18].

3. Environmental Impact

Table 3. shows the effect of fly ash use on the environment in concrete.

Scenario	Cement Used (kg/m³)	CO_2 Emissions (kg/m³)	Reduction (%)
Conventional (no fly ash)	350	600	0
With 30% Fly Ash Replacement	245	420	30
With 40% Fly Ash Replacement	210	360	40

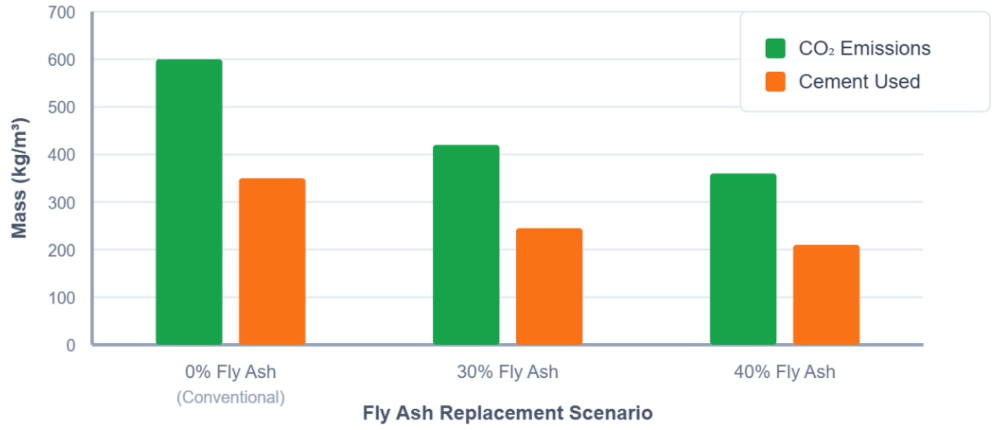

Figure 5: Environmental Savings in Concrete: Fly Ash Incorporation in Cement Consumption and CO_2 Emissions.

Replacing 30-40% of cement with fly ash can result in a 40-percent decrease in carbon footprint of concrete, and save huge quantities of industrial wastes going to landfills [21].

4. Microstructural and Surface Modification Effects

Mecano-chemical (MC) modification of fly ash has been reported to improve the reactivity of fly ash by reducing the particle size, enhancing the surface area, and partially amorphizing the fly ash [8]. The fly ash that is MC-treated is more soluble in the alkaline solutions, thereby promotes quicker and more complete pozzolanic reactions [8]. Morphological changes and decreased crystallinity after treatment are verified with the help of SEM and XRD [8].

5. Fly Ash Composites: Mechanical Properties

Composites made with metals (e.g., Al alloys) and polymers as fly ash have:

- ➢ Higher tensile and compressive strength: load transfer and stiffness increase with optimum fly ash content [5].
- ➢ Improved hardness and wear resistance: fly ash particles increase hardness and wear resistance which is useful in structural and wear sensitive applications [5], [20].
- ➢ Low density: fly ash has a low density, which makes the composites lightweight and this is beneficial in automotive and aerospace components [5].

But, the overloading of fly ash may cause a condition of agglomeration of particles, high porosity and poor mechanical performance [5].

6. Machine Learning for Mix Optimization

Machine learning approaches, such as regression tree ensembles and gradient boosting, have achieved high accuracy in predicting concrete porosity and optimizing mix designs with SCMs [23]. These models account for complex interactions among mix variables (e.g., water/binder ratio, fly ash content, curing conditions), enabling data-driven optimization for targeted properties.

7. Agricultural and Industrial Waste based Composite Cement.

The addition of fly ash to agricultural fibre (e.g., coconut fibre) is shown in studies to have synergistic benefits to composite cements [25]. Compositions optimised improve compressive strength and modulus of rupture and decrease density and water absorption. The goal of combining various waste streams is in line with the ideals of the circular-economy.

8. Difficulties with Large-Scale Implementation.

- ➢ Quality variability: the fact that the chemical and physical properties of fly ash may vary significantly among different sources requires proper characterization and quality management [3], [7].
- ➢ Standardisation: national and international standards need harmonisation to make sure that performance is reliable and easily accepted in the market [2].
- ➢ Early-age strength: high levels of fly ash can be such that it requires more curing or activation measures to attain the desired early-age properties [22].
- ➢ Durability guarantee: monitoring of the field performance over a long period of time is required to authenticate the laboratory results and guarantee lifecycle durability [13].

CONCLUSION AND RECOMMENDATIONS

- Fly ash is a lightweight, renewable and usable in civil engineering as it has great technical and environmental benefits when used as a part of the concrete, road and composite construction. Key findings include:
- 15-40% fly ash as a partial substitute of cement does not affect or impair compressive strength and performance of concrete, particularly at older ages.
- Fly ash enhances resistance to chemical attack, permeability is decreased and microstructure is refined to increase the service life.
- Applications of soil stabilisation and pavements enjoy the advantage of greater loading and moisture resistance.
- Construction materials have a significant environmental impact that can be minimised by means of cement replacement and waste valorisation.
- Surface modification method can also be used to increase the reactivity and performance of fly ash e.g. MC treatment.
- Machine learning can use the data to optimise mix designs, which can be predicted and efficient.
- The addition of both agricultural and industrial by-products to the composite cements increases the aspect of sustainable construction.

Nonetheless, there are still issues in quality inconsistency, standardisation, strength building in early age and durability guaranteeing. Future studies need to concentrate on:

- Establishing strong protocols in the characterization of fly ash and its quality management.
- Extraregional standardisation of specifications to ease adoption.
- Developing surface modification and activation processes on low-reactivity fly ash.
- The use of machine learning and big-data analytics to design a mix and lifecycle assessment.
- Increasing use of fly ash in high-technology composites and infrastructure, which ensures the shift towards a circular construction economy.

By doing so, construction industry will be able to achieve the maximum potential of fly ash as a pillar of sustainable development.

REFERENCES

[1] P. Adamiec, J.C. Benezet, and A. Benhassaine, “Relation entre une cendre volante silico-alumineuse et son charbon,” *Poudres & Grains*, vol. 15, no. 3, pp. 35–46, 2005. [Online]. Available: http://arxiv.org/pdf/1111.6847v1

[2] Chong Cao, “Machine Learning-based Prediction of Porosity for Concrete Containing Supplementary Cementitious Materials,” 2021. [Online]. Available: http://arxiv.org/pdf/2112.07353v1

[3] P. Adamiec et al., “Relation entre une cendre volante silico-alumineuse et son charbon,” *Poudres & Grains*, 2005.

[4] D.C. Adriano, A.L. Page, A.A. Elseewi, A.C. Chang, and I. Straughan, “Utilization and Disposal of Fly Ash and Other Coal Residues in Terrestrial Ecosystems: A Review,” *J. Environ. Qual.*, vol. 9, 1979, pp. 333-344.

[5] Mainak Saha, “Fly ash composites: A review,” 2022. [Online]. Available: http://arxiv.org/pdf/2202.11167v1

[6] C. F. Lin, H. C. His, “Resource Recovery of Waste Fly ash: Synthesis of Zeolite-like Materials,” *Environ. Sci. Technol.*, vol. 29, 1995, pp. 1109-1117.

[7] V.M. Malhotra, “Making concrete greener with fly ash,” *Concr. Int.*, vol. 21, 1999, pp. 61-66.

[8] Kunihiko Kato, Yunzi Xin, Takashi Hitomi, and Takashi Shirai, “Surface modification of fly ash by mechano-chemical treatment,” *Ceram. Int.*, vol. 45, 2019, pp. 849–853. [Online]. Available: http://arxiv.org/pdf/2202.01779v1

[9] M.H. Shehata, M.D.A. Thomas, “The effect of Fly ash composition on the expansion of concrete due to alkali–silica reaction,” *Cem. Concr. Res.*, vol. 30, 2000, pp. 1063-1072.

[10] A. Palomo, M.W. Grutzeck, M.T. Blanco, “Alkali-activated fly ashes: A cement for the future,” *Cem. Concr. Res.*, vol. 29, 1999, pp. 1323-1329.

[11] S. Kumar, R. Kumar, "Mechanical activation of fly ash: Effect on reaction, structure and properties of resulting geopolymer," *Ceram. Int.*, vol. 37, 2011, pp. 533-541.

[12] J. Davidovits, "Geopolymers and geopolymeric materials," *J. Therm. Anal. Calorim.*, vol. 35, 1989, pp. 429-441.

[13] N. Moreno, X. Querol, J.M. Andrés, K. Stanton, M. Towler, H. Nugteren, M. Janssen-Jurkovicova, and R. Jones, "Physico-chemical characterization of Spanish fly ashes," 2000.

[14] P. K. Rohatgi, "Low-cost, fly-ash-containing aluminum-matrix composites," *JOM*, vol. 46, no. 11, pp. 55–59, 1994.

[15] G.S. Ryu, Y.B. Lee, K.T. Koh, Y.S. Chung, "The mechanical properties of fly ash-based geopolymer concrete with alkaline activators," *Constr. Build. Mater.*, vol. 47, 2013, pp. 409-418.

[16] D. Hardjito, S.E. Wallah, D.M.J. Sumajouw, B.V. Rangan, "On the Development of Fly Ash-Based Geopolymer Concrete," *ACI. Mater. J.*, vol. 101, 2004, pp. 467-472.

[17] N. I. M. Nadzri, J. B. Shamsul, M. N. Mazlee, "Development and properties of composite cement reinforced coconut fiber with the addition of fly ash," 2012. [Online]. Available: http://arxiv.org/pdf/1705.00179v1

[18] O. Hjelmar, "Leachate from land disposal of coal fly ash," *Waste. Manag. Res.*, vol. 8, 1990, pp. 429-449.

[19] J. Binner et al., "Selection, processing, properties and applications of ultra-high temperature ceramic matrix composites, UHTCMCs–a review," *International Materials Reviews*, vol. 65, no. 7, pp. 1–56, 2019.

[20] A. Mayurbhai Desai, T. Rudra Paul, and M. Mallik, "Mechanical properties and wear behavior of fly ash particle reinforced Al matrix composites," *Mater. Res. Express*, vol. 7, p. 16595, 2020.

[21] V.M. Malhotra, "Making concrete greener with fly ash," *Concr. Int.*, vol. 21, 1999.

[22] S. Kumar, R. Kumar, "Mechanical activation of fly ash: Effect on reaction, structure and properties of resulting geopolymer," *Ceram. Int.*, vol. 37, 2011.

[23] Chong Cao, "Machine Learning-based Prediction of Porosity for Concrete Containing Supplementary Cementitious Materials," 2021.

[24] A. Palomo, S. Alonso, A.F. Jiménez, I. Sobrados, J. Sanz, "Alkaline Activation of Fly Ashes: NMR Study of the Reaction Products," *J. Am. Ceram. Soc.*, vol. 87, 2004, pp. 1141-1145.

[25] N. I. M. Nadzri, J. B. Shamsul, M. N. Mazlee, "Development and properties of composite cement reinforced coconut fiber with the addition of fly ash," 2012.

[26] D.K. Gupta, U.N. RaiRudra, D.T. Inouhe, "Impacts of fly-ash on soil and plant responses," *J. Plant. Res.*, vol. 115, 2002, pp. 401-409.

[27] J. Davidovits, "GEOPOLYMER Chemistry & Applications," Institute GEOPOYMERE, 2008.

[28] J. Temuuji, R.P. Williams, A.V. Riessen, "Effect of mechanical activation of fly ash on the properties of geopolymer cured at ambient temperature," *J. Mater. Process. Tech.*, vol. 209, 2009, pp. 5276-5280.

[29] N.Marjanovic, M. Komljenović, Z. Baščarević, V. Nikolić, "Improving reactivity of fly ash and properties of ensuing geopolymers through mechanical activation," *Constr. Build. Mater.*, vol. 57, 2014, pp. 151-162.

[30] D. Hardjito, S.E Wallah, D.M.J. Sumajouw, B.V. Rangan, "Factors Influencing The Compressive Strength of Fly Ash-based Geopolymer Concrete," *Civil Engineering Dimension*, vol. 6, 2004, pp. 88-93.

[31] A. F. Jimenez, A. Palomo, "Composition and microstructure of alkali activated Fly ash binder: Effect of the activator," *Cem. Concr. Res.*, vol. 35, 2005, pp. 1984-1992.

[32] M. Mallik and M. Saha, "Carbon-Based Nanocomposites: Processing, Electronic Properties and Applications," Springer, Singapore, 2021.

[33] C. R. P. Rao, M. S. Bhagyashekar, and N. Viswanath, "Machining Behavior of Al6061-Fly Ash Composites," *Procedia Materials Science*, vol. 5, pp. 1593–1602, 2014.

[34] P. K. Rohatgi, R. Q. Guo, P. Huang, and S. Ray, "Friction and abrasion resistance of cast aluminum alloy-fly ash composites,"

Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, vol. 28, no. 1.

[35] S. B. Prabu, L. Karunamoorthy, S. Kathiresan, and B. Mohan, "Influence of stirring speed and stirring time on distribution of particles in cast metal matrix composite," *Journal of Materials Processing Technology*, vol. 171, no. 2, pp. 268–273, 2006.

[36] J. Binner, et al., "Selection, processing, properties and applications of ultra-high temperature ceramic matrix composites, UHTCMCs–a review," *International Materials Reviews*, vol. 65, no. 7, pp. 1–56, 2019.

[37] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," *J. Therm. Anal. Calorim.*, vol. 37, 1991, pp. 1633.

[38] G. Ferraiolo, M. Zilli, A. Converti, "Fly ash disposal and utilization," *J. Chem. Technol. Biotechnol.*, vol. 47, 1990, pp. 281-305.

[39] S. Sudarshan and M. K. Surappa, "Dry sliding wear of fly ash particle reinforced A356 Al composites," *Wear*, vol. 265, pp. 349–360, 2008.

[40] D. Hardjito, S.E. Wallah, D.M.J. Sumajouw, B.V. Rangan, "On the Development of Fly Ash-Based Geopolymer Concrete," *ACI. Mater. J.*, vol. 101, 2004, pp. 467-472.

[41] J. Raut *et al.* , "Performance optimization of hybrid nano-engineered geopolymer binders-based ultra-high-performance concrete," *Nano-Structures & Nano-Objects* , vol. 42, p. 101469, Mar. 2025, doi: 10.1016/j.nanoso.2025.101469.

[42] S. P. M. Pérez, J. J. Lozano-Sánchez, D. M. Ramírez-Silva, and J. E. Vallejos-Madianero, "Use and effect of fly ash in concrete: A literature review," *Revista Facultad de Ingeniería Universidad de Antioquia* . Universidad de Antioquia, Oct. 09, 2023. doi: 10.17533/udea.redin.20230927.

[43] M. P. Vikram, "Evaluation of Fly Ash as a Partial Replacement for Cement in Concrete: Effects on Strength and Durability," International *Journal for Research in Applied Science and Engineering Technology* , vol. 12, no. 12, p. 1123, Dec. 2024, doi: 10.22214/ijraset.2024.65992.

[44] Z. F. Akbulut, D. Yavuz, T. A. Tawfik, P. Smarzewski, and S. Güler, "Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review," Sustainability, vol. 16, no. 12. Multidisciplinary Digital Publishing Institute, p. 4905, Jun. 07, 2024. doi: 10.3390/su16124905.

[45] G. Li *et al.* , "Fly Ash Application as Supplementary Cementitious Material: A Review," *Materials* , vol. 15, no. 7. Multidisciplinary Digital Publishing Institute, p. 2664, Apr. 05, 2022. doi: 10.3390/ma15072664.

[46] S. Saloni *et al.* , "Performance of rice husk Ash-Based sustainable geopolymer concrete with Ultra-Fine slag and Corn cob ash," *Construction and Building Materials* , vol. 279, p. 122526, Feb. 2021, doi: 10.1016/j.conbuildmat.2021.122526.

[47] A. Nawaz, P. Julnipitawong, and S. Tangtermsirikul, "Effect of Curing Temperature and Free Lime Content in Fly Ash on Basic Properties and Autoclave Expansion of Fly Ash Mixtures," *Engineering Journal* , vol. 27, no. 10, p. 67, Oct. 2023, doi: 10.4186/ej.2023.27.10.67.