

Research Article

Eco-mechanical performance of fly ash-modified concrete blocks: strength development and CO₂ emission assessmentBasirul Alam Sarker Ovy^{1*} , Md. Abul Bashar² , Md. Al Imran Hossan¹

ABSTRACT: Fly ash is a waste product from coal combustion and can be used as a partial substitute for cement, thereby aiding in the production of lower-carbon-footprint concrete. Most studies have focused only on mechanical or environmental performance, and fewer studies are available that integrate properties of fly ash concrete in terms of mechanical performance, water absorption and CO₂ emissions at low replacement rates ($\leq 20\%$). Accordingly, this study aims to meet this need by developing an integrated eco-mechanical evaluation to identify a practical replacement criterion based on three indicators. Five mixtures with varying amounts of fly ash (0%, 5%, 10%, 15% and 20%) were developed. The compressive strength, splitting tensile strength and water absorption after 28 days were tested in the laboratory, while the cradle-to-gate CO₂ emission was calculated by calculating the CO₂ emission from every constituent of the concrete. These results indicate that the 5% fly ash was able to achieve about 94.3% compressive strength of the control mixture, while also reducing CO₂ emissions by 4.71%, yielding the best strength-carbon balance of the mixtures. Increased replacement levels resulted in higher emission reduction, up to 18.85% at 20% fly ash, while producing more significant strength reductions. The findings serve as the basis for policy and specific specifications that would be associated with appropriate utilization of locally available fly ash in accordance with strength and durability requirements. It could be encouraged through material availability, transport, processing, quality control and the possibility of cement savings at the project level, through financial incentives or procurement preferences and performance-based standards.

Keywords: Fly ash, Concrete blocks, Mechanical performance, Waste utilization, Eco-efficient concrete

1. INTRODUCTION

Portland cement is one of the most significant construction materials in the world [1]. The cement sector contributes around 8 per cent to global CO₂ emissions per year [2]. This number puts the cement industry in the top 10 among the biggest emissions sources by industry worldwide [3]. The main source of emissions in the clinker production process is the emission of CO₂ directly into the atmosphere from this process, which is estimated to be around 0.83 tonnes of CO₂ formed for every tonne of clinker formed [4]. High-speed urbanization, population growth, and infrastructure development, especially in developing and emerging economies (DEEs), remain drivers of global demand for cement [5]. With this increased demand, it is essential to find more productive materials that can partially be used instead of cement but have the same mechanical strength and durability as concrete [6]. To counter these responses, researchers and engineers have worked on alternative cementing materials which can reduce the amount of clinker that can be used in a concrete mixture [7]. Waste materials from the industrial process, such as fly ash, crushed granulated blast-furnace slag, and silica fume, are also being used to replace cement, and rice husk ash is another such product derived from the agricultural process [6], [8]. While the replacement of the causative constituents of fly-ash can yield desired mechanical and durability characteristics in high-volume fly-ash concrete, the use of

OPEN ACCESS

Affiliation

¹Department of Farm Structure and Environmental Engineering, Bangladesh Agricultural University, Mymensingh-2202, Bangladesh.

²SAARC Agriculture Centre, Dhaka-1215, Bangladesh.

*Correspondence

Email: basirul.ovy.iifs@gmail.com

ORCID

Basirul Alam Sarker Ovy: 0009-0007-2889-632X

Md. Abul Bashar: 0009-0000-5770-4090

Md. Al Imran Hossan: 0009-0001-3272-9678

Article history

Received: September 19, 2026

Revised: September 26, 2026

Accepted: October 4, 2026

How to cite

Ovy, B. A. S., Bashar, Md. A., Hossan, MD. Al. I., (2026). Eco-mechanical performance of fly ash-modified concrete blocks: strength development and CO₂ emission assessment. Journal of Applied Materials and Technology, 8(2), 75–82. <https://doi.org/10.65794/Jamt.8.2.75-82>.

Copyright (c) 2026 Basirul Alam Sarker Ovy, Md. Abul Bashar, Md. Al Imran Hossan. This article is licensed under a [Creative Commons Attribution 4.0 International License](#).



more fly-ash content can cause a delay in early-age strength expansion linked to ordinary Portland cement concrete [9]. An important research objective for sustainable use of concrete is the reduction of Portland cement content with the required mechanical properties and long-term durability [10].

Reducing a construction's carbon footprint is important to meet the Paris Agreement [11]. One of the most industrially achievable and at the same time the most implemented methods to reduce the environmental impact of concrete is the replacement of Portland cement with secondary cementitious materials [12]. Partial replacement of cement can help the environment only if the replacement material is environmentally friendly and the percentage of replacement is sufficient. For instance, by adding fly ash as 30% of the cement mass, Yaseen et al. [13] found a 29% reduction in global warming potential of the concrete. The results demonstrated the potential of using these industrial by-products in the production of sustainable concrete mixes as supplementary cementitious materials (SCMs), as this further reinforced the possibility [14].

Fly ash is a solid residue formed when coal is burned for electricity generation in thermal power stations [15]. Volz [16] estimates that around 800 million tonnes of fly ash were being produced each year, on a global scale, making it a significant industrial waste material. Due to limited utilization, significant portions of fly ash will be stored or disposed of, leading to a scarcity of land and potentially causing harm to the environment around the disposal sites [17]. The partial substitution of Portland cement with fly ash provides a beneficial use for this industrial by-product while reducing conventional cement consumption and the associated environmental burden [18].

The reactive silica and alumina stages in fly ash respond with the calcium hydroxide generated by the process of cement hydration, resulting in the generation of more binding phases and helping to develop the cementitious matrix. [19]. Continued pozzolanic activity generates additional binding phases, contributing to the later-age strength and durability of fly-ash concrete [20]. With proper design, the high-volume fly ash concrete can be designed to be comparable to the compressive strength, permeability and resulting long-term durability of conventional cement concrete, especially in the presence of aggressive exposure conditions [9].

The mechanical response of fly ash concrete (FAC) could vary significantly due to the variations in fly ash dosage, mix design, water-to-binder ratio, and curing practices [21]. Class F fly ash has mostly pozzolanic properties, and the presence of higher levels of calcium in the Class C fly ash results in self-cementing activities in addition to pozzolanic activities [22]. Kim et al. [23] evaluated the potential of using nano-silica and silica fume as nanotechnology additives for enhancing the hydration rate of the binders and initial mechanical characteristics for high-FA binders. The changes have expanded the scope and applicability of fly ash concrete in real structures such as concrete tiles, paver blocks, precast and mass concrete structures, where fly ash can make a significant contribution to sustainability, lower heat in the concrete, and enhance long-term durability [21], [24]. The use of partial fly ash decreases the amount of Portland cement required, which can help to decrease the carbon footprint of concrete [25]. Life-cycle assessments reveal that partial additional of cement with fly ash has the potential to lower the climate change and acidification impacts while also reducing primary energy use [26]. The compensations of using fly

ash concrete are highest when the fly ash is sourced from a reasonable transportation distance and when fly ash replaces Portland cement, because too far transportation of fly ash will either jeopardize the carbon-saving effect of fly ash substituting Portland cement or offset it [27]. The comprehensive mechanical and environmental benefits make fly ash a very extensively studied and practically applied material for sustainable construction of concrete [28].

The cement industry is dominant in Asia, with China being the largest producer, and other major players in the region being India, Vietnam and Indonesia [29]. Urbanization and infrastructure development are contributing to the increasing demand for cement and concrete in many Asian developing countries [30]. Hence, embracing sustainable and eco-friendly materials for buildings is crucial in Asia to minimize the environmental footprint and promote sustainable development [31]. Several countries have started promoting the use of recycled and industrial by-products in construction materials to support the goal of the circular economy, landfill pressure reduction and resource efficiency [32]. China and India are among the countries that are significant producers of coal fly ash; both countries have encouraged its use in cement, concrete, construction materials and other building applications via policies and regulations [15], [33]. Fly ash is now being used in sustainable applications of concrete in Southeast Asia for rigid pavement construction to decrease the amount of cement required and manage coal-combustion waste [34]. The results of these regional initiatives highlight the potential for large-scale implementation of eco-friendly material substitution while providing a promising new focus for the growth of suitable standards and material supply chain infrastructure [29].

The use of interlocking paving blocks with fly ash and AFBs like rice husk ash has attracted the attention of researchers as a sustainable paving material [35]. Research has recently been conducted to use fly ash as a material in pervious pavement blocks to enhance the infiltration performance and to reduce the ingesting of cement and CO₂ emissions [36]. The usage of fly ash and rice husk ash in permeable concrete can contribute to sustainability without compromising the strength. They are advantageous for low-cost, low-carbon paving in Asian cities, particularly in the aspect of stormwater control and waste reduction [37].

This study does not introduce the use of fly ash as a partial replacement for cement, as it is already a well-established method. Previous studies often separate the concepts of strength and embodied carbon. However, other research has been dedicated to high-volume and pervious or geopolymers systems [9], [36], [37]. Little attention has been focused on small to moderate replacement levels (5-20%) in the conventional 1:2:4 concrete used for blocks. There are few studies that incorporate locally available Class F fly ash and evaluate both mechanical strength and water absorption and carbon emissions. The main objective of this study is to test OPC concrete using 0%, 5%, 10%, 15% & 20% fly ash with a fixed w/b ratio of 0.55. Compressive and splitting tensile strength were evaluated at 7, 14 and 28 days. It also assessed 28-day water absorption as an indirect measure of open capillary porosity and calculated the cradle-to-gate embodied CO₂ for every mix. The results collectively reveal a range of replacement over which carbon savings can be achieved without significant loss of strength and gain in absorption. This is valid for the tested conditions and is not indicative of a single optimum dosage.

Table 2. Characterization of fly ash based on experimental investigation

Sl.	Characteristics	Experimental Value / Observation
1	Type of fly ash	Class F fly ash
2	SiO ₂	50.04%
3	Al ₂ O ₃	29.62%
4	Fe ₂ O ₃	9.78%
5	SiO ₂ + Al ₂ O ₃ + Fe ₂ O ₃	87.44%, satisfying ASTM Class F requirement
6	CaO	4.44%, indicating low-calcium fly ash
7	Specific gravity	2.18
8	Unit weight (Kg/m ³)	620
9	Fineness (% passing No. 325 sieve)	99.98%

2. MATERIALS AND METHODS

2.1. Materials. Ordinary Portland cement (Premium Brand) and fly ash were used as the binder constituents, while river sand, coarse aggregate, and potable water completed the concrete mixture. The fly ash sample was taken from the Meghna Group of Industries in Narayanganj, Bangladesh. Five concrete mixtures were produced by substituting fly ash for cement at mass-based replacement levels of 0%, 5%, 10%, 15%, and 20% (i.e., 0, 20, 40, 60, and 80 kg/m³ of fly ash, respectively). The concrete was produced using river sand with a fineness modulus of 1.61, along with locally sourced khoa passing the 9.53 mm sieve. Water of suitable quality was used for preparing and curing the specimens.

Table 1. Physical characteristics of cement based on bangladeshi representative cement samples [38].

Cement Property	Observed Range
Standard consistency	28 - 32%
Initial setting period	120 - 180 min
Final setting period	195 -240 min

2.2. Characterization of fly ash. Before the experimental analysis, moisture was removed from the collected fly ash by heating it in an oven at 97 °C for 24 hours. The specific gravity of fly ash was determined using a pycnometer. Unit weight was designed as the ratio of weight to volume. The fineness of fly ash was determined by sieving through a No. 325 sieve. The consistency of fly ash-cement paste was measured using the Vicat apparatus. The measured specific gravity, unit weight, and fineness of the fly ash are reported in Table 2.

2.3. Concrete mixture design. Concrete was organized using a nominal mix ratio of 1:2:4 for cement, fine aggregate, and coarse aggregate, respectively. Fly ash was used as partial replacement of cement at different percentages. The water content and the corresponding water-to-binder (w/b) ratio of each mixture are reported alongside the material quantities. The quantities of materials used are shown in Table 3.

2.4. Fresh concrete workability. The fresh concrete mixture was slump tested to check workability before casting. The slump value obtained was 1.45 in. equivalent to 37mm, which is a low-slump concrete mix (Fig. 1). All the cylindrical specimens were cast with uniform consolidation and free from entrapped air during casting.

2.5. Specimen preparation and test preparation. Based on the mix sizes given in Table 3, five different concrete mix combinations were made. The coarse aggregate (khoa) was soaked in water before mixing to ensure the condition was saturated surface dry (SSD). The fly ash and cement were first dry blended to create a homogenous binding material. The specimens were air-dried for two to three minutes before the fine and coarse aggregates were placed together in a hand mixer and the binder was added to the mixture. About half of the required amount of water was then added, and then the second half of the water, for a total of 2–3 minutes of mixing, it was mixed until a homogeneous product was formed. The fresh concrete was placed in another cylindrical mould of 75mm diameter and 150mm height for the CS, STS and WA tests. The filling of the moulds was divided into two parts; the concrete was tamped with a tamping rod after each stage to get the minimum amount of entrapped air. The fresh concrete was tested using a standard slump cone setup immediately after mixing, which is known as a slump test. A total of 100 cylinders has been prepared for the whole ex-

**Figure 1.** Slump test of concrete mix.



Figure 2. Sample preparation and test setup: (a) Casted concrete cylinders, (b) CS tests, (c) SPS tests, (d) Water absorption tests.

Table 3. Material quantities adopted for producing 20 concrete blocks (Kg/m^3).

Sample No.	Mix Code	Cement/ OPC	Sand, S	Khoa/ Coars Aggregate, CA	Fly Ash, FA	Fly Ash (%)	Water (Kg/m^3)	w/b ratio
1	C100	400	706	1173	0	0	220	0.55
2	FA5	380	706	1173	20	5	220	0.55
3	FA10	360	706	1173	40	10	220	0.55
4	FA15	340	706	1173	60	15	220	0.55
5	FA20	320	706	1173	80	20	220	0.55

perimental program (Figure 2). After 24 hours in the moulds, the cylinders were removed and stored in water until testing at 7 or 28 days. Before testing, the specimen ends were prepared to provide level loading surfaces and were allowed to reach a surface-dry condition under laboratory conditions. Finally, its compressive strength (CS) and splitting tensile strength (STS) were measured using a universal testing machine. The compressive strength of each cylinder was measured when an axial load was applied till the cylinder broke. The strength obtained was determined as $f_c = (P/A)$, where P is the maximum load, A is the loaded cross-sectional area, and also for a cylindrical specimen, $A = \pi D^2/4$, where D is the diameter of the cylinder. The cylindrical specimen was placed horizontally in the STS test with the longitudinal axis perpendicular to the applied load. The splitting tensile strength was determined by applying Eq. $f_t = 2P/\pi LD$, where P , L , and D were the maximum load actually applied, cylinder length, and cylinder diameter, respectively. The WA test was carried out by soaking oven-dried cylinders in water for 24 hours and measuring the percentage increase in weight of the cylinder. The number of specimens cast-off for each test is summarized in Table 4.

Table 4. Quantity of cylindrical block.

Test	Specimen type	Dimensions (dia. x hig.)	Curing ages	Total specimens
Compressive Strength	Cylinder	75 x 150 mm	7, 28 days	45
Splitting Tensile Strength	Cylinder	75 x 150 mm	7, 28 days	45
Water Absorption	Cylinder	75 x 150 mm	28 days	10

3. RESULT AND DISCUSSION

3.1. Compressive strength. As the fly ash cement content increased, the compressive strengths decreased monotonously after 7 and 28 days. The control mixture achieved the highest compressive strengths, reaching 18.86 MPa after 7 days and 22.99 MPa after 28 days (see Fig.3). When 5% of the cement was replaced with fly ash, the 28-day strength decreased to 21.67 MPa, representing a 5.74%

reduction relative to the control. However, when more fly ash was added, strength resistance was significantly lowered. The 28-day compressive strength was reduced to 10.40 MPa, which is 54.76% less than the control mixture when replacing the fly ash with 20%. This finding is similar to previous research [9], [13]. There are two reasons for the loss of strength. First, fly ash dilutes the concentration of cement, causing the concentration of calcium silicate hydrate to be reduced during the early stage. Secondly, the low calcium content of Class F fly ash results in a slow reaction [19], [22]. The slow gain in strength of the fly ash is due to the low content of CaO in it 4.44%. This behaviour is generally observed in low Calcium Fly Ash Concrete [20], [21]. Thus, the ideal percentage of replacement of fly ash in the investigated mixtures was 5%, which showed almost a balanced strength performance.

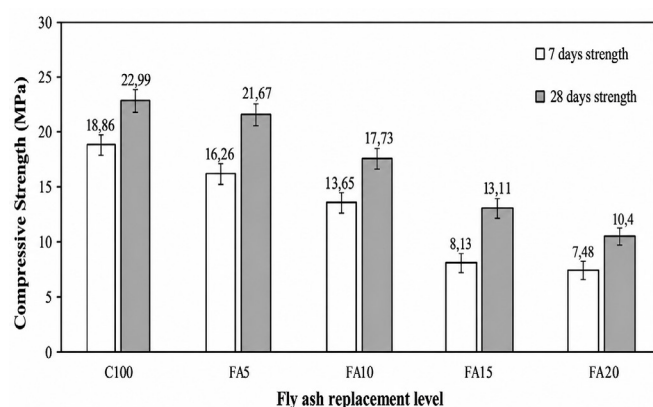


Figure 3. Compressive strength results at 7 and 28 days.

3.2. Splitting tensile strength. From the Figure 4, FA5 showed the highest splitting tensile strength of 3.09 MPa, exceeding the control value of 2.52 MPa by approximately 22.6%; however, further increases in fly ash content resulted in lower strength. At 28 days, the control mixture achieved the highest strength of 3.99 MPa, followed by FA5, FA10, FA15, and FA20 with 3.45, 3.02, 2.46, and 1.92 MPa, respectively. Relative to the control, the 28-day strength reductions were 13.5%, 24.3%, 38.3%, and 51.9% for FA5, FA10, FA15, and FA20. After 7 and 28 days, all mixtures had improved, as it was established that the cure period continued the process of binder formation. Although the mixture containing 5% fly ash showed improved tensile strength, further increases in the replacement level caused a gradual decline at the investigated ages. Fly ash (FA) can be used to enhance both matrix packing and interfacial bonding due to small quantities without adversely affecting the early hydration process [22]. Nevertheless, an increase in replacement levels depletes the amount of binder and slows the pozzolanic reaction, thus decreasing the tensile resistance [9].

3.3. Water absorption. The outcome of fly ash content on the water absorption of concrete specimens is shown in Fig. 5. The water absorption of the mixture was continuously increasing from 5.74% for the control mixture to 8.12% with 20% replacement of fly ash. Water absorption continued to increase in line with an increasing percentage of fly ash ranging from 5 to 20%, with an increase of 20.21 to 41.46% compared with the control sample. Absorption

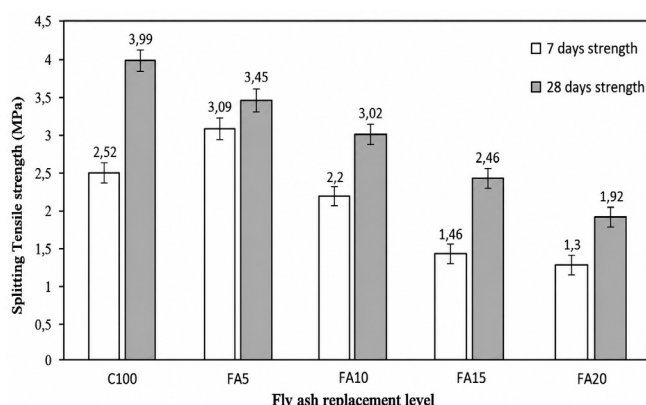


Figure 4. Splitting tensile strength results at 7 and 28 days.

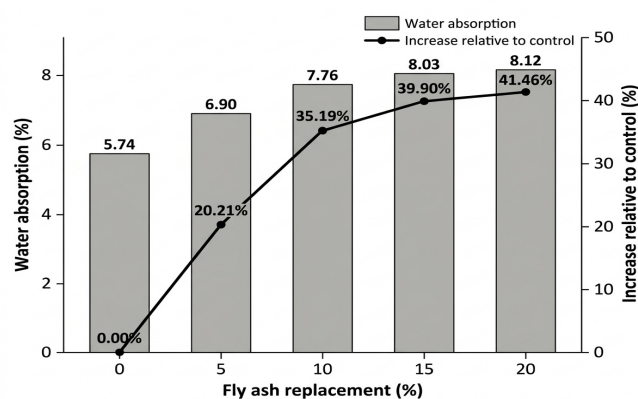


Figure 5. 28-Day water absorption water consumption results.

increased most steeply up to the 10% replacement level, after which the rate of increase slowed: only a 0.09 percentage-point gain was observed between the 15% and 20% mixes, even though the absolute absorption value continued to rise. Overall, the 28-day results showed that water absorption increased as the fly ash replacement level rose. This suggests that more open capillary networks are obtained at higher fly ash contents [9]. Nevertheless, given that all specimens were tested at 28 days, this trend was observed early, before any significant pozzolanic reaction; no direct measurement of the porosity (such as mercury intruded porosimetry) was conducted, so the absorption should be considered an indirect indicator of the open capillary porosity, and not as a direct measure of the total porosity. Fly ash concrete usually compacts the pore network at advanced ages (56 - 90 days) by secondary hydration. Lower early hydration and unreacted fly ash result in a coarser capillary network [20], [21]. This effect creates a durability concern that needs to be balanced with the carbon savings.

3.4. Environmental assessment. The most suitable assessments for evaluating concrete's ecological characteristics were energy consumption and carbon footprint [2]. The embodied-carbon calculation used separate emission coefficients for cement, fly ash, fine aggregate, coarse aggregate, and water, sourced from the NSW Government's 2025 concrete guidance [39] (Table 5).

Table 5. Reference CO₂ emission factors for concrete constituents.

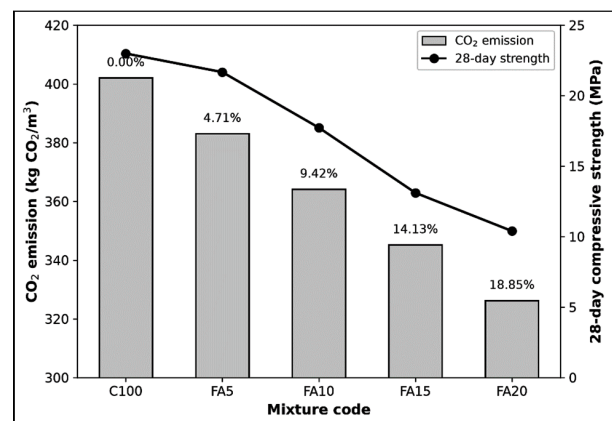
Concrete Constituent.	Symbol	Emission Factor, Kg CO ₂ -Eq/Tonne	Emission Factor, Kg CO ₂ -Eq/Kg
Cement / PCC	EF_{PCC}	966.9	0.9669
Fly ash	EF_{FA}	19.8	0.0198
Fine Aggregate / Sand	EF_S	4.2	0.0042
Coarse Aggregate / Khoa	EF_{CA}	10.5	0.0105
Water	EF_W	0.4	0.0004

Table 6. Eco-mechanical performance assessment of fly ash-modified concrete mixtures based on 28-day compressive strength and CO₂ emission.

Mix Code	Fly ash	28-days CS, $f_{c,28}$ (Mpa)	CO ₂ Emission, EI (Kg CO ₂ /m ³)	CO ₂ Reduction (%)	Mechanical Performance Index, MI_i	Environmental Performance Index, EI_i	Eco-mechanical Performance Index, EMI_i
C100	0	22.99	402.04	0.00	1.000	1.000	0.0572
FA5	5	21.67	383.10	4.71	0.943	1.050	0.0566
FA10	10	17.73	364.16	9.42	0.771	1.105	0.0487
FA15	15	13.11	345.22	14.13	0.570	1.167	0.0380
FA20	20	10.40	326.27	18.85	0.452	1.236	0.0319

The factors are adapted from NSW Government guidance, which is Australian and the investigated materials are sourced from Bangladesh. This geographical mismatch is an analytical limitation. The absolute results are not intended to be generalized as Bangladesh-specific environmental product data as it can be used for a consistent comparison between the five mixtures under a common factor set. Further research is needed to incorporate region-specific life-cycle inventory data such as local cement production, crushed-brick aggregate production, electricity, processing, and transport.

The environmental presentation of the fly ash-modified concrete mixtures was assessed through CO₂ emission intensity and the compressive strength at 28 days. The total CO₂ emission was determined by multiplying the emission factor for each constituent material by its unit mass. The calculated CO₂ emission was reduced from 402.04 kg CO₂/m³ of the control mixture to 326.27 kg CO₂/m³ of the mixture with 20% fly ash, with a maximum reduction of 18.85% (Table 6). This reduction could be largely attributed to the reduction in cement content, as cement had the maximum CO₂ emission factor among the constituent materials. However, the enhanced fly ash replacement level caused the gradual decrease in compressive strength. The 5% fly ash mixture yielded the best strength-Carbon trade-off, as the compressive strength of this mixture was retained at 94.3% of the control sample after a 28-day period of curing and was 4.71% lower in CO₂ emission than the control sample (Fig. 6). Although the control mix (C100) attains the highest absolute eco-mechanical performance index (0.0572), marginally above FA5 (0.0566), FA5 represents the practical trade-off optimum: it retains 94.3% of the compressive strength while reducing embodied CO₂ by 4.71%. This trend is in line with the previous life-cycle assessment [13], [25]. According to Shah et al. [12], using secondary materials instead of cement can reduce CO₂ emissions by up to 1.3 gigatons per year around the world.

**Figure 6.** Environmental assessment of different type of mixtures at 28 days.

The findings solidify that there's a trade-off between mechanical performance and carbon savings. FA5 demonstrated the optimal balance with 94.3% compressive strength retention and 4.71% CO₂ reduction. CO₂ was reduced by 9.42% in FA10, with greater water absorbability and loss of strength. The replacement range of 5–10% thus seems most feasible for concrete blocks only where the associated strength reduction and higher water absorption of FA10 can be tolerated [9], [20]. The data provided are early-age results. The strength and durability at both 56 and 90 days can increase due to the pozzolanic reaction [13], [19].

4. CONCLUSION

A consistent trend from 5–20% fly ash replacement was observed with respect to reductions in embodied CO₂ (decreasing from 402.04 kg CO₂e/m³ (control) to 326.27 kg CO₂e/m³ (FA20), loss in compression and 28-day tensile strengths and increased water absorption. For the best properties, the recommended mix is FA5, with a 94.3% ability to retain the 28-day compressive strength (21.67 MPa) and a 3.45 MPa 28-day splitting tensile strength, along with a CO₂ saving of 4.71%. While its absolute performance index (eco-mechanical) 0.0566 is slightly lower than the control 0.0572, its practical performance profile in terms of trade-off strength–carbon makes it the best in class. The replacement ratio of 10% (FA10) improves CO₂ savings to 9.42%, but results in a loss of 22.9% in 28-day compressive strength and higher water absorption, requiring careful consideration of this change for intended use, where the lower compressive strength is tolerable. It can be recommended that FA5 can be used in the 5–10% replacement range since it exhibits higher 7-day splitting tensile strength and retained 94.3% of 28-day compressive strength with 4.71% CO₂ saving. The conclusions are restricted to the low age of data and one fly ash source, and lack microstructural and transport-property data. Future studies should assess the strength and durability at 56 and 90 days, characterise the porosity, sorptivity and capillary absorption, and confirm with emission factors that are more representative for the region and other fly ash sources.

■ ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the Department of Farm Structure, Bangladesh Agricultural University and the laboratory staff for their technical assistance and support during the experimental work.

■ CREDIT AUTHOR STATEMENT

Basirul Alam Sarker Ovy: Conceptualization, Methodology, Investigation, Writing-Original Draft, Writing-Review and Editing. **Md. Abul Bashar:** Supervision, Resources, Writing-Review and Editing. **Md. Al Imran Hossan:** Formal Analysis, Data Curation, Visualization, Writing-Review and Editing. All authors have read and approved the published version of the manuscript.

■ DECLARATIONS

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

■ AVAILABILITY OF DATA

No new data were generated or analyzed in this study. Accordingly, no datasets are associated with this manuscript.

■ AI DISCLOSURE STATEMENT

The authors used Claude and Gemini during preparation of this work to check grammar and improve the writing quality. The authors reviewed and edited the work as necessary and take full responsibility for the final version.

■ REFERENCES

- [1] V. V. Nguyen et al., “Low-Density Geopolymer Composites for the Construction Industry,” *Polymers*, vol. 14, no. 2, p. 304, Jan. 2022, doi: [10.3390/polym14020304](https://doi.org/10.3390/polym14020304).
- [2] G. Habert et al., “Environmental impacts and decarbonization strategies in the cement and concrete industries,” *Nat Rev Earth Environ*, vol. 1, no. 11, pp. 559–573, Sep. 2020, doi: [10.1038/s43017-020-0093-3](https://doi.org/10.1038/s43017-020-0093-3).
- [3] P. Friedlingstein et al., “Global Carbon Budget 2020,” *Earth Syst. Sci. Data*, vol. 12, no. 4, pp. 3269–3340, Dec. 2020, doi: [10.5194/essd-12-3269-2020](https://doi.org/10.5194/essd-12-3269-2020).
- [4] M. Antunes, R. L. Santos, J. Pereira, P. Rocha, R. B. Horta, and R. Colaço, “Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review,” *Materials*, vol. 15, no. 1, p. 209, Dec. 2021, doi: [10.3390/ma15010209](https://doi.org/10.3390/ma15010209).
- [5] S. O. Bonney, J. Song, M. Liphadzi, and K. O. Adjei, “Modelling and Forecasting Concrete Demand for Sustainable Infrastructure Development in Developing Economies: Evidence from Ghana,” *Buildings*, vol. 16, no. 4, p. 850, Feb. 2026, doi: [10.3390/buildings16040850](https://doi.org/10.3390/buildings16040850).
- [6] J. He, S. Kawasaki, and V. Achal, “The Utilization of Agricultural Waste as Agro-Cement in Concrete: A Review,” *Sustainability*, vol. 12, no. 17, p. 6971, Aug. 2020, doi: [10.3390/su12176971](https://doi.org/10.3390/su12176971).
- [7] S. Von Greve-Dierfeld et al., “Understanding the carbonation of concrete with supplementary cementitious materials: a critical review by RILEM TC 281-CCC,” *Mater Struct*, vol. 53, no. 6, p. 136, Dec. 2020, doi: [10.1617/s11527-020-01558-w](https://doi.org/10.1617/s11527-020-01558-w).
- [8] M. Firdous and B. Singh, “Supplementary cementitious materials in concrete and associated structural and environmental benefits: A review,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 889, no. 1, p. 012077, Nov. 2021, doi: [10.1088/1755-1315/889/1/012077](https://doi.org/10.1088/1755-1315/889/1/012077).
- [9] D. Runganga, F. Okonta, and I. Musonda, “Strength and Durability Properties of High-Volume Fly Ash (HVFA) Binders: A Systematic Review,” *CivilEng*, vol. 5, no. 2, pp. 435–460, May 2024, doi: [10.3390/civileng5020022](https://doi.org/10.3390/civileng5020022).
- [10] T. A. Fode, Y. A. Chande Jande, and T. Kivevele, “Effects of different supplementary cementitious materials on durability and mechanical properties of cement composite – Comprehensive review,” *Heliyon*, vol. 9, no. 7, p. e17924, Jul. 2023, doi: [10.1016/j.heliyon.2023.e17924](https://doi.org/10.1016/j.heliyon.2023.e17924).
- [11] C. Karakosta and J. Papathanasiou, “Decarbonizing the Construction Sector: Strategies and Pathways for Greenhouse Gas Emissions Reduction,” *Energies*, vol. 18, no. 5, p. 1285, Mar. 2025, doi: [10.3390/en18051285](https://doi.org/10.3390/en18051285).
- [12] I. H. Shah, S. A. Miller, D. Jiang, and R. J. Myers, “Cement substitution with secondary materials can reduce annual global CO₂ emissions by up to 1.3 gigatons,” *Nat Commun*, vol. 13, no. 1, p. 5758, Sep. 2022, doi: [10.1038/s41467-022-33289-7](https://doi.org/10.1038/s41467-022-33289-7).
- [13] N. Yaseen, S. Alcivar-Bastidas, M. Irfan-ul-Hassan, D. M. Petroche, A. U. Qazi, and A. D. Ramirez, “Concrete incorporating supplementary cementitious materials: Temporal evolution of compressive strength and environmental life cycle assessment,” *Heliyon*, vol. 10, no. 3, p. e25056, Feb. 2024, doi: [10.1016/j.heliyon.2024.e25056](https://doi.org/10.1016/j.heliyon.2024.e25056).

- [14] S. Sakir, S. N. Raman, Md. Safiuddin, A. B. M. A. Kaish, and A. A. Mutalib, "Utilization of By-Products and Wastes as Supplementary Cementitious Materials in Structural Mortar for Sustainable Construction," *Sustainability*, vol. 12, no. 9, p. 3888, May 2020, doi: [10.3390/su12093888](https://doi.org/10.3390/su12093888).
- [15] V. K. Yadav et al., "Status of Coal-Based Thermal Power Plants, Coal Fly Ash Production, Utilization in India and Their Emerging Applications," *Minerals*, vol. 12, no. 12, p. 1503, Nov. 2022, doi: [10.3390/min12121503](https://doi.org/10.3390/min12121503).
- [16] J. S. Volz, "High-Volume Fly Ash Concrete for Sustainable Construction," *AMR*, vol. 512–515, pp. 2976–2981, May 2012, doi: [10.4028/www.scientific.net/AMR.512-515.2976](https://doi.org/10.4028/www.scientific.net/AMR.512-515.2976).
- [17] D. Das and P. K. Rout, "A Review of Coal Fly Ash Utilization to Save the Environment," *Water Air Soil Pollut*, vol. 234, no. 2, p. 128, Feb. 2023, doi: [10.1007/s11270-023-06143-9](https://doi.org/10.1007/s11270-023-06143-9).
- [18] Y. Miao et al., "The Effect of Industrial Byproducts Fly Ash and Quartz Powder on Cement Properties and Environmental Benefits Analysis," *Applied Sciences*, vol. 15, no. 9, p. 5093, May 2025, doi: [10.3390/app15095093](https://doi.org/10.3390/app15095093).
- [19] G. L. Golewski, "The Role of Pozzolanic Activity of Siliceous Fly Ash in the Formation of the Structure of Sustainable Cementitious Composites," *Sustainable Chemistry*, vol. 3, no. 4, pp. 520–534, Dec. 2022, doi: [10.3390/suschem3040032](https://doi.org/10.3390/suschem3040032).
- [20] F. U. A. Shaikh and S. W. M. Supit, "Compressive strength and durability properties of high volume fly ash (HVFA) concretes containing ultrafine fly ash (UFFA)," *Construction and Building Materials*, vol. 82, pp. 192–205, May 2015, doi: [10.1016/j.conbuildmat.2015.02.068](https://doi.org/10.1016/j.conbuildmat.2015.02.068).
- [21] Y.-C. Choi, "Hydration and Mechanical Properties of High-Volume Fly Ash Cement under Different Curing Temperatures," *Materials*, vol. 17, no. 19, p. 4716, Sep. 2024, doi: [10.3390/ma17194716](https://doi.org/10.3390/ma17194716).
- [22] Z. F. Akbulut, D. Yavuz, T. A. Tawfik, P. Smarzewski, and S. Guler, "Enhancing Concrete Performance through Sustainable Utilization of Class-C and Class-F Fly Ash: A Comprehensive Review," *Sustainability*, vol. 16, no. 12, p. 4905, Jun. 2024, doi: [10.3390/su16124905](https://doi.org/10.3390/su16124905).
- [23] B.-J. Kim, G.-W. Lee, and Y.-C. Choi, "Hydration and Mechanical Properties of High-Volume Fly Ash Concrete with Nano-Silica and Silica Fume," *Materials*, vol. 15, no. 19, p. 6599, Sep. 2022, doi: [10.3390/ma15196599](https://doi.org/10.3390/ma15196599).
- [24] S. K. Sahu, S. Kamalakkannan, and P. K. Pati, "Fly ash utilization in concrete tiles and paver blocks," in *New Materials in Civil Engineering*, Elsevier, 2020, pp. 897–917. doi: [10.1016/B978-0-12-818961-0.00030-2](https://doi.org/10.1016/B978-0-12-818961-0.00030-2).
- [25] K. C. Onyelowe et al., "Global warming potential-based life cycle assessment and optimization of the compressive strength of fly ash-silica fume concrete; environmental impact consideration," *Front. Built Environ.*, vol. 8, p. 992552, Oct. 2022, doi: [10.3389/fbuil.2022.992552](https://doi.org/10.3389/fbuil.2022.992552).
- [26] R. Kurda, J. D. Silvestre, and J. De Brito, "Toxicity and environmental and economic performance of fly ash and recycled concrete aggregates use in concrete: A review," *Heliyon*, vol. 4, no. 4, p. e00611, Apr. 2018, doi: [10.1016/j.heliyon.2018.e00611](https://doi.org/10.1016/j.heliyon.2018.e00611).
- [27] K. R. O'Brien, J. Ménaché, and L. M. O'Moore, "Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption," *Resources*, vol. 18, no. 1, pp. 621–629, Nov. 2009, doi: [10.1007/s11367-009-0105-5](https://doi.org/10.1007/s11367-009-0105-5).
- [28] G. Li et al., "Fly Ash Application as Supplementary Cementitious Material: A Review," *Materials*, vol. 15, no. 7, p. 2664, Apr. 2022, doi: [10.3390/ma15072664](https://doi.org/10.3390/ma15072664).
- [29] D. Cheng et al., "Projecting future carbon emissions from cement production in developing countries," *Nat Commun*, vol. 14, no. 1, p. 8213, Dec. 2023, doi: [10.1038/s41467-023-43660-x](https://doi.org/10.1038/s41467-023-43660-x).
- [30] J. A. Olsson, S. A. Miller, and M. G. Alexander, "Near-term pathways for decarbonizing global concrete production," *Nat Commun*, vol. 14, no. 1, p. 4574, Jul. 2023, doi: [10.1038/s41467-023-40302-0](https://doi.org/10.1038/s41467-023-40302-0).
- [31] R. Liong, S. D. Puspitasari, F. S. Binhudayb, and S. Hesham, "Advancements in Green Materials for Concrete in South East Asia: A Mini Review," *Trop. Environ. Biol. Technol.*, vol. 2, no. 1, pp. 44–56, Jun. 2024, doi: [10.53623/tebt.v2i1.441](https://doi.org/10.53623/tebt.v2i1.441).
- [32] B. K. Shukla et al., "Sustainable construction practices with recycled and waste materials for a circular economy," *Asian J Civ Eng*, vol. 25, no. 7, pp. 5255–5276, Nov. 2024, doi: [10.1007/s42107-024-01111-y](https://doi.org/10.1007/s42107-024-01111-y).
- [33] Y. Luo, Y. Wu, S. Ma, S. Zheng, Y. Zhang, and P. K. Chu, "Utilization of coal fly ash in China: a mini-review on challenges and future directions," *Environ Sci Pollut Res*, vol. 28, no. 15, pp. 18727–18740, Apr. 2021, doi: [10.1007/s11356-020-08864-4](https://doi.org/10.1007/s11356-020-08864-4).
- [34] F. M. Suryani, S. Rizal, A. Abdullah, and M. Isya, "Fly Ash Substitution in Lightweight Concrete for Rigid Pavement Construction on Low-Bearing-Capacity Soil," *Sustainability*, vol. 15, no. 21, p. 15239, Oct. 2023, doi: [10.3390/su152115239](https://doi.org/10.3390/su152115239).
- [35] T. Bilir, B. F. Aygun, J. Shi, O. Gencel, and T. Ozbakkaloglu, "Influence of Different Types of Wastes on Mechanical and Durability Properties of Interlocking Concrete Block Paving (ICBP): A Review," *Sustainability*, vol. 14, no. 7, p. 3733, Mar. 2022, doi: [10.3390/su14073733](https://doi.org/10.3390/su14073733).
- [36] S. Supit, K. Boonserm, and Priyono, "Mechanical properties and environmental impact assessment of eco-friendly pervious pavement blocks containing high-volume fly ash," *City Built Enviro*, vol. 3, no. 1, p. 16, Aug. 2025, doi: [10.1007/s44213-025-00057-4](https://doi.org/10.1007/s44213-025-00057-4).
- [37] D. N. Subramaniam and N. Sathiparan, "Comparative study of fly ash and rice husk ash as cement replacement in pervious concrete: mechanical characteristics and sustainability analysis," *International Journal of Pavement Engineering*, vol. 24, no. 2, p. 2075867, Jan. 2023, doi: [10.1080/10298436.2022.2075867](https://doi.org/10.1080/10298436.2022.2075867).
- [38] M. F. Asef, K. S. Ahmed, and M. Ahmed, "Physical and Strength Properties of Cements Manufactured in Bangladesh: A Case Study," *MIJST*, vol. 10, pp. 49–59, Jun. 2022, doi: [10.47981/j.mijst.10\(01\)2022.319\(49-59\)](https://doi.org/10.47981/j.mijst.10(01)2022.319(49-59)).
- [39] NSW Government, "How to calculate the embodied carbon of a concrete mix - factsheet," 2025.