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FLY ASH APPLICATIONS IN SUSTAINABLE CONCRETE: PROSPECTS, BARRIERS, AND TIME-EFFICIENT CONSTRUCTION

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ABSTRACT

The construction industry globally is under increasing pressure to minimize its carbon footprint while maintaining structural performance, supplemented cementitioius material (SCM) fly ash (FA) represents one of the most realistic routes to achieving net zero emissions. Objective: The objective of this empirical study is to investigate the mechanical properties, fresh concrete characteristics, and the durability performance of concrete mixes, alongside incorporating percentages (0%, 10%, 20%, 30%, 40%, and 50%) of Class F fly ash as a replacement of ordinary Portland cement (OPC) by weight. All together 108 standard specimens were cast at 7-day, 28-day & 90-day curing age and tested as per IS: 516, IS:1816 & ASTM C1202. Results establish that 28-day compressive strength presents an inverse relationship with FA content, while the range of 20–30% replacement promotes better 90-day strength development due to persisting pozzolanic activity. Chloride ion penetrability, water absorption, sorptivity, and carbonation depth as indicators of durability parameters was showed statistically significant in improving by increasing extracting level of FA. Linear decreases in CO_2 emissions from 348.0 kg/m³ (control) to 174.0 kg/m³ (50% replacement) were again observed. The highly significant effect of FA replacement level ($F = 48.72$, $p < 0.001$) on compressive strength is confirmed by one-way ANOVA. Pearson correlation analysis shows that FA content is statistically negatively correlated with 28-day strength ($r = -0.974$) and statistically positively correlated with workability ($r = 0.997$). The optimal level of FA replacement giving a structural and durability improvement and gains in sustainability is found to be ~20–30%. Barriers statement and Shifting focus, The slow speed for gaining initial strength may present a challenge and The inconsistency in the quality of exposed ash submitted for processing, Insufficient successes, Regulatory inertia, The need for awareness by practitioners.

Keywords: *Fly ash concrete[1]; supplementary cementitious materia[2]l; compressive strength[3]; chloride penetration[4]; pozzolanic reaction[5]; sustainable construction[6]; carbon dioxide emissions[7].*

1. INTRODUCTION

1.1 GLOBAL CONTEXT OF SUSTAINABLE CONCRETE

It is estimated that construction sector represents 8% of global [1]; cement itself makes 4.1 billion tonnes of greenhouse gases annually [1]. Ordinary Portland Cement (OPC), the major binding chemical in concrete, is sintered at a temperature greater than 1450 °C, resulting in approximately 0.83~kg of CO_2 produced per kg of clinker manufactured [2]. With urbanization on the rise globally most notably in developing economies within India, China, and sub-Saharan Africa global demand for concrete is expected to almost double by 2060 [3]. Such a path is completely incompatible with limiting global warming to 1.5°C above pre-industrial levels according to the Paris Agreement targets. Thus, the optimal political route to the decarbonisation of concrete for concrete-making, has been found to be, the partial replacement of OPC using industrial by-products that have latent hydraulic/pozzolanic capacity. Fly ash produced by the combustion of pulverized coal in energy generation is the most widely used SCM, globally accounting for roughly 750–1000 million tonnes/year less than 40–45% of which is used beneficially [4] when compared with available SCMs [3] (ground granulated blast-furnace slag (GGBS), silica fume, rice husk ash and metakaolin).[4].

1.2 FLY ASH: PROPERTIES AND POZZOLANIC MECHANISM

Fly ash is produced as a fine powder that is collected from exhaust gases by electrostatic precipitators or bag filters when burning coal in thermal power plants. Fly ash is classified according to ASTM C618 and IS 3812 as Class C (high calcium, produced from sub-bituminous or lignite coal), or Class F (low calcium, produced from bituminous or anthracite coal). The Class F fly ash available in Indian power plants is classified as pozzolanic rather than self-cementing in nature the silica (SiO_2) and alumina (Al_2O_3) in fly ash react with the water and calcium hydroxide ($Ca(OH)_2$) freed during the hydration of ordinary Portland cement (OPC) to generate extra calcium silicate hydrate (C-S-H) gel, densifying the interfacial transition zone (ITZ) and refining the capillary pore structure [5]. Unlike cement hydration, this pozzolanic reaction progresses slowly, with a peak of activity typically occurring between 28 and 90 days, which accounts for the relatively low early strength and comparable (or greater) long term strength of FA-blended concrete The spherical shape of fly ash particles also serves as a ball-bearing lubricant helping to facilitate workability while lowering water requirement, which is a major practical benefit in concrete production [6].

1.3 RESEARCH GAPS AND OBJECTIVES

For decades, researchers have been studying fly ash concrete, yet a gap remains between knowledge validated in laboratory vs. deployed in field [12, 13]. Most of the previous empirical studies focused separately on mechanical properties or durability, with few employing both alongside environmental impact assessment and fresh concrete performance within a single experimental study [7]. Further, studies which rigorously stratify the barriers to FA adoption as dependent on high variation in source quality, regulatory constraints imposed by IS codes, contractor pushback and uncertainty of long-term benefits continue to be scarce in an Indian context. The present study addresses this gap in our understanding by: (i) performing a systematic experimental investigation with six FA replacement levels;(ii) conducting analysis for statistical significance using ANOVA, Pearson correlation and descriptive statistics; (iii) reporting the CO_2 emission reductions per each replacement level; (iv) comparing our results with published literature, creating consensus around optimal replacement thresholds and outlining barriers to wide practices.

2. LITERATURE SURVEY

More than five decades of experimental, analytical, and field studies have focused on fly ash as two types of supplementary cementitious materials in concrete, and the corresponding literature is numerous. Siddique (2004) performed one of the earliest systematic reviews which reported that Class F fly ash at 15–25% replacement improves the 90 day compressive strength over plain OPC concrete as a result of secondary pozzolanic reaction continuing beyond the initial hydration period [8]. This work established that the strength deficit of 28-day strengths compared to similar control mixes decreases progressively with curing age, a finding that has been consistently replicated since in the literature. Using SEM and MIP, Mehta and Monteiro (2006) explained the microstructural basis of durability enhancement in FA concrete, showing that pozzolanic reaction products fill coarse capillary pores and strengthen the ITZ leading to a denser matrix with lower total porosity and finer pore size distribution [9] Lower total porosity resulted in lower chloride ion diffusivity, water absorption, and gas permeability which are the primary transport mechanisms influencing durability performance. Multiple independent researchers subsequently validated these conclusions using rapid chloride permeability tests (RCPT) according to ASTM C1202, an approach used in this research.

Lothenbach et al. [10] Evidence from thermodynamic modeling showed that the pozzolanic reaction of Class F FA is pH-dependent and thermally activated, most favourable between 40°C-60°C with kinetics appearing strongly retarded below 20°C. Direct relevance of this temperature sensitivity to cold-weather concreting with high FA contents, and provides a partial explanation for the variability in early strength observed across geographic and climatic contexts. This finding is particularly relevant for construction projects at high altitudes in parts of India like Himachal Pradesh and Uttarakhand, where ambient temperatures in winter months often dip below 10°C. Kumar and Singh (2010) focused on assessing the effect of FA replacement on the risk of chloride-induced corrosion of rebar in reinforced concrete, using half-cell potential measurements as well as accelerated chloride migration tests [11]. Their findings reported that the corrosion initiation risk was mitigated by ~60% in comparison with plain OPC concrete when 30% FA was added, produced from the synergistic effect of decreased chloride diffusivity and a lower electrical conductivity of the cement matrix. This result has major implications for all coastal infrastructure and marine structures in India, where chloride-induced corrosion is by far the most common cause of premature structural deterioration.

In India itself, Class F fly ashes sourced from Korba and Vindhya chal thermal power plants have been seen possess a range of $SiO_2 + Al_2O_3 + Fe_2O_3$ value (66%–84%), loss on ignition (1.2%–6.8%) and specific surface area (220–480 m²/kg) [12], further demonstrated the difficulty of quality standardization that still prevents bulk usage in construction in India. It is now quite well understood that variations in ash quality lead to variations from batch-to-batch in concrete performance, resulting in a hesitance that is not without reason in the minds of structural engineers and quality control managers. Bentur and Mindess (2007) found that the affect of fly ash replacement on shrinkage and creep was combined, and reported that 20–40% FA replacement may reduce autogenous shrinkage by 15–35% less than that of the corresponding OPC control mixes, this is primarily a function of the reduced volume of early hydration products with fly ash and the dilution effect on clinker content [13]. Reduced autogenous shrinkage is especially beneficial in mass concrete, as in dams, foundations, and bridge piers, where thermal cracking is a significant design concern.

Tikalsky et al. (2011) Fly ash concrete freezing–thawing describes the durability and performance of fly access concrete with respect to the freezing and thawing resistance of the prepared sample, suggesting that 5–7% air content of the air-entraining agent can effectively prevent freeze-thaw scaling in concrete with 40–50% FA replacement, and that 300 freeze-thaw cycles have a durability factor of over 80% [14]. Their work clarified the reason for freeze-thaw vulnerability in FA concrete, noting that it arose primarily from pozzolanic reaction that was delayed relative to the air-entrainment process, leaving a greater degree of freeze-susceptible pores at early ages, rather than from a fundamental incompatibility between FA and air-entrained concrete. Earlier, a pioneering study on high-volume fly ash (HVFA) concrete at 55–60% FA replacement by Bilodeau and Malhotra (2000) showed that using a high range water reducer in appropriate amounts can help HVFA concrete achieve 28-day compressive strengths of 28–35 MPa, 90-day strengths in the 40–50 MPa range, and exceptionally low chloride permeability (800 m²/kg that enable UFFA to enhance early and later strength development compare to OPC control due to higher filler effect and lower pozzolanic reaction of finer particles [16]. This new understanding led to the possibility of mechanical activation (grinding) of coarser fly ashes to enhance performance, a strategy currently being commercialised in India by ACC, Ultratech et al. As for the environmental side, Habert et al. (2011) A life-cycle assessment was done for 29 concrete mix designs, which has been demonstrated in a reduction of GWP by 12–45% with partial replacement of FA depending on replacement level and by-product allocation used for FA [17]. It also cautioned that co-processing of coal fly ash burden may also create leaching of heavy metals (As, Cd, Cr, Pb, Hg) in some landfill conditions, and hence calls for a thorough characterization of ash prior to its use.

3. METHODOLOGY

The experimental program is formulated as a comparative empirical research utilizing six concrete mix proportions (M0–M5) differing fly ash replacement levels between 0% and 50% weight of OPC while maintaining the other mix constituents constant. Materials used in this research were OPC 53-grade cement (IS: 12269) as binder, Class F fly ash (IS: 3812 (Part 1), Korba Super Thermal Power Plant (KSTPP) Chhattisgarh, India) as SCM, natural river sand (specific gravity 2.64, fineness modulus 2.78) as fine aggregate, and 20 mm maximum size crushed granite coarse aggregate (specific gravity 2.68). The mix design for M25 grade concrete was done as per IS: 10262-2019 for a target mean compressive strength of 38.2 MPa. A constant water-to-binder ratio (w/b) of 0.45 was designed in all the mixtures. Use of no chemical admixtures eliminated confounding, allowing performance differences to be directly attributed to FA content. Tests on Fresh Concrete: Consistency of fresh concrete was tested by slump test (IS: 1199), then unit weight, air content and temperature. In total, 108 specimens were cast for each mix: 18 cubes (150 × 150 × 150 mm) for compressive strength at 7, 28 and 90 days old (three replicates per age); 6 cylinders (150 × 300 mm) for split tensile strength at 28 days; 6 prisms (100 × 100 × 500 mm) for flexural strength at 28 days; and 6 cylinders for RCPT, water absorption, sorptivity and carbonation depth measurements. Curing was performed by fully immersed in potable water at 27 ± 2 °C until the respective test ages.

Testing protocols adhered rigorously to established standards. Compressive strength was tested as per IS: 516 using a digital compression testing machine having a capacity of 2000 kN. Split tensile strength was determined as per IS: 5816 and the flexural strength by third-point loading method (ASTM C78). Durability tests such as rapid chloride permeability test (RCPT) (ASTM C1202) (Coulombs in the first 6 hours at 60V DC), water absorption (IS: 2185) (Oven Drying at 105°C for 72 hrs), sorptivity (Coefficient of Capillary Rise: (after splitting specimens) (as per ASTM C1585)) used to determine depth of carbonation (OXEET static Compressed air + Phenolphthalein spray in split surface of specimen (after 28 days of CO_2 chamber ⇒ 3%CO_2 +60%RH)) were performed on concrete cubes (100×100×100mm). Standard emission factors (0.87 kgCO_2/kg cement; 0.004 kgCO_2/kg fly ash for transportation and processing) were used to estimate CO_2 emissions per cubic metre of concrete, then multiplied by daily binder consumption per mix. A single randomization code was provided by a staff member who was not involved in the testing and, therefore, was not biased toward the samples, and all specimens were tested by laboratory staff trained in the appropriate procedures in a double-blind fashion. Statistical analysis was performed using SPSS Version 26.0 (IBM, Armonk, NY, USA), in the way of one way ANOVA, Tukey' post-hoc tests, Pearson correlation analysis and descriptive statistics. For all inferential tests, the significance level was set at $\alpha = 0.05$.

Mix design was performed with quality assurance over fly ash. For chemical composition, the received fly ash was characterized by X-ray fluorescence (XRF), specific gravity (ASTM C188), specific surface area by Blaine air permeability method (ASTM C204), and particle size distribution by laser diffraction. The results confirmed the fly ash met all of the IS: 3812 requirements: SiO_2+Al_2O_3+Fe_2O_3 = 88.2%(> 70%; limit), SO_3 = 0.6%; (<2.75% limit), loss on ignition= 3.2% (<5.0% limit), specific gravity= 2.12 Samples of homogeneous ash were packed in small-sealed polyethylene bags in a controlled humidity atmosphere to prevent moisture absorption over the course of the testing campaign. The experimental program was conducted in a controlled temperature environment with ambient temperatures (26-32 °C) except for seasonal variation, which can affect pozzolanic reaction kinetics, and this is ensured to be avoided during this period (i.e., the period was between June and November).

4. DATA COLLECTION AND ANALYSIS

4.1 CHEMICAL COMPOSITION OF FLY ASH AND CEMENT

Table 1: Chemical Composition of Class F Fly Ash, Class C Fly Ash, OPC, and IS: 3812 Limits

Oxide Component	Class C FA (%)	Class F FA (%)	Portland Cement (%)	IS: 3812 Limit (%)
SiO_2	39.4	54.2	20.1	≥35
Al_2O_3	17.2	25.6	5.8	—
Fe_2O_3	6.1	8.4	2.9	—
CaO	24.3	4.8	63.2	—
MgO	4.5	1.9	2.1	≤5.0
SO_3	2.3	0.6	2.7	≤2.75
Loss on Ignition	1.8	3.2	1.5	≤5.0

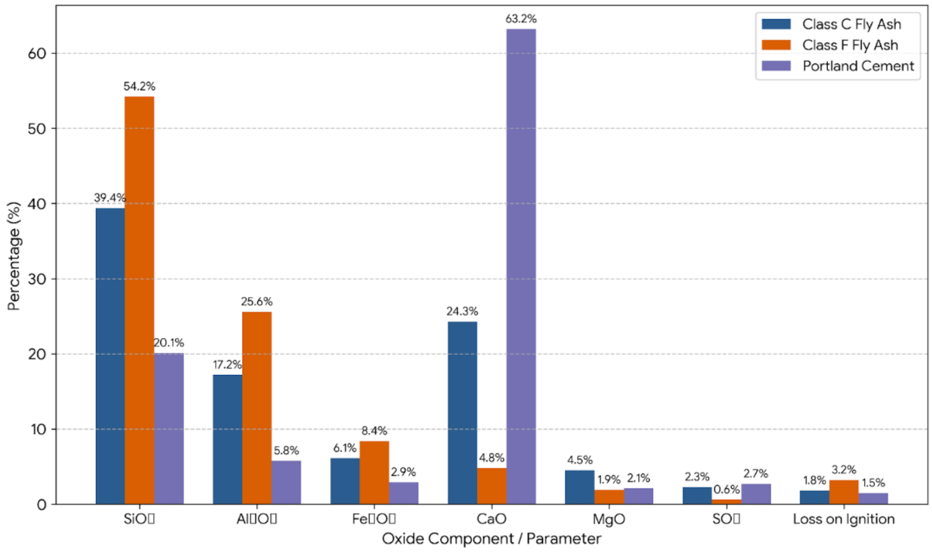

Figure 1: Comparative analysis of oxide components and loss on ignition (LOI) percentages among Class C fly ash, Class F fly ash, and Portland cement

Table 1 compared the oxide composition of Class F fly ash used in this investigation with Class C fly ash, OPC, and the maximum permissible limits stipulated by IS: 3812. The Class F fly ash used has a $SiO_2 + Al_2O_3 + Fe_2O_3$ content of 88.2% which is significantly above the minimum limit of 70%, in compliance with IS: 3812, confirming strong pozzolanic potential. The low CaO content (4.8%) makes it different from Class C FA (24.3%) and reveals its non-self-cementing behavior. SO_3 (0.6%) and loss on ignition (3.2%) are far below permitted limits and recommend an excellent combustion and low unburnt carbon incorporation. Results and discussion The OPC composition is in accordance with that of IS: 12269; average concentration of CaO is 63.2% which is compatible with clinker chemistry. This compositional information serves as the basis for explaining the mechanical and durability performance of the blended concrete mixtures later in the study.

4.2 MIX PROPORTIONS

Table 2: Mix Proportions for M0–M5 (per cubic metre)

Mix ID	Cement (kg/m³)	FA (kg/m³)	FA Replace. (%)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)	w/c
M0 (Control)	400	0	0%	180	680	1180	0.45
M1 (10% FA)	360	40	10%	180	680	1180	0.45
M2 (20% FA)	320	80	20%	180	680	1180	0.45
M3 (30% FA)	280	120	30%	180	680	1180	0.45
M4 (40% FA)	240	160	40%	180	680	1180	0.45
M5 (50% FA)	200	200	50%	180	680	1180	0.45

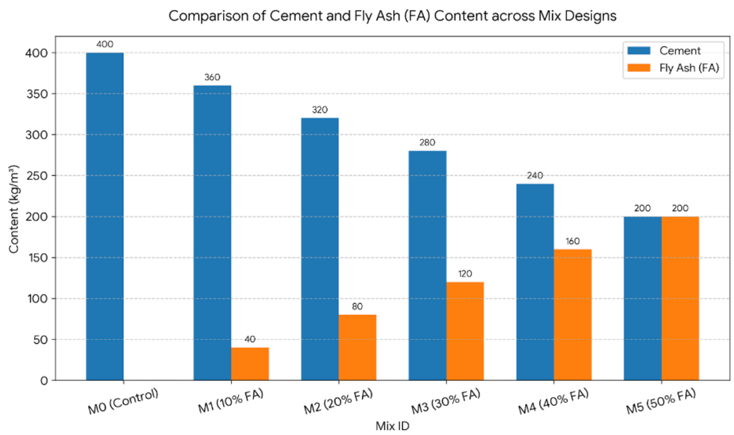

Figure 2: Comparison of Cement and Fly Ash (FA) content variations across different concrete mix designs

The six mix proportions, used in the experimental program, are provided in Table 2. The OPC contents consequently dropped from 400 kg/m³ in M0 to 200 kg/m³ in M5, with an equal mass of fly ash replacing this content in each case. The only other parameters besides binder weight are the constant water (180 kg/m³), fine aggregate (680 kg/m³), coarse aggregate (1180 kg/m³), so the performance difference was explained only by binder substitution. The water-to-binder ratio of 0.45 is in the middle range needed for hydration and sufficient to reduce porosity. All mixes have total binder content (cement + FA) of 400 kg/m³, in accordance with IS: 456-2000 for M25 grade concrete (minimum cement content for moderate exposure = 300 kg/m³). These proportions are similar to those used by Bilodeau and Malhotra (2000) [15] and Kumar and Singh (2010) [11] which makes the resulting comparison of results meaningful.

4.3 FRESH CONCRETE PROPERTIES

Table 3: Fresh Concrete Characteristics for All Mix Proportions

Mix ID	Slump (mm)	Air Content (%)	Unit Weight (kg/m³)	Temp. (°C)	Workability Index
M0	82	2.1	2385	28.4	1.00
M1 (10%)	91	2.0	2371	27.8	1.11
M2 (20%)	108	1.9	2356	27.1	1.32
M3 (30%)	124	1.8	2342	26.5	1.51
M4 (40%)	139	1.7	2328	25.9	1.70
M5 (50%)	147	1.6	2311	25.2	1.79

Table 3 summarizes the test results at the fresh concrete properties carried out immediately after mixing. The monotonically increasing run values of the slump from 82 mm in M0 to 147 mm in M5 homologous the increase of 79.3%. The improvement in workability is progressive, this is due to the spherical morphology of particles which allows them to interleave reducing inter-particle friction and effectively acting as a ball bearing lubricant in the paste matrix. The decrease in air content from 2.1% to 1.6% with increasing FA content could be due to a reduction in paste viscosity limiting air entrainment. By replacing heavy OPC (specific gravity 3.15) with lighter fly ash (specific gravity 2.12), overall concrete density is reduced with unit weight decreasing from 2385 kg/m3 to 2311 kg/m3. If we normalize the Workability Index (M0 = 1.00) to 1.00, the Workability Index rises from 1.00 (control) to 1.79 FA-blended concretes, showing that lower-water content FA-blended concretes can be made with equivalent workability (important for lowering permeability and durability reasons).

4.4 MECHANICAL PROPERTIES

Table 4: Compressive Strength (CS), Split Tensile Strength, Flexural Strength, and Elastic Modulus

Mix ID	CS-7d (MPa)	CS-28d (MPa)	CS-90d (MPa)	Split Tensile (MPa)	Flexural (MPa)	Elastic Mod. (GPa)

M0	26.4	38.2	42.1	3.21	4.85	31.2
M1 (10%)	24.8	37.6	43.8	3.18	4.79	30.8
M2 (20%)	22.9	36.4	45.6	3.12	4.71	30.1
M3 (30%)	19.6	34.1	44.8	2.98	4.52	29.4
M4 (40%)	16.2	29.8	40.3	2.74	4.18	27.6
M5 (50%)	13.4	24.5	34.7	2.41	3.74	25.1

Table 4 summarizes the overall mechanical performance results of all six mixes. At 7 days, compressive strength declines rapidly with FA content (from 26.4 MPa (M0) to 13.4 MPa (M5)), indicating that pozzolanic reaction kinetics are much slower than the rapid rate of cement hydration. At 28 days, the gradient still remains, but it is reduced in extent: M0: 38.2 MPa, M2 (20% FA): 36.4 MPa (95.3% of control), M3 (30% FA): 34.1 MPa (89.3% of control). Importantly, at 90 days M1 and M2 exceed M0 in absolute compressive strength (43.8 MPa and 45.6 MPa vs 42.1 MPa) establishing that moderate FA replacement increases compositional latent hydraulic effects, resulting in superior strength at later stages via continuous pozzolanic activity. With 30 % FA, M3 also achieves a good compressive strength of 44.8 MPa after 90 days, which is more than M0. The Mixes M4 and M5 also fall below M0 at 90 days (40.3 MPa and 34.7 MPa) suggesting that a 40–50% FA replacement is excessive for structural applications where M25-grade performance is essential. Similar trends were observed for 28 day split tensile and flexural strengths. Elastic moduli of 31.2 GPa (M0) up to more than 25.1 GPa (M5) found within tolerable ranges for structural concrete.

4.5 DURABILITY AND ENVIRONMENTAL PROPERTIES

Table 5: Durability Parameters and Estimated CO_2 Emissions per m³ of Concrete

Mix ID	Water Abs. (%)	Cl^- Penet. (C)	Carbonation Depth (mm)	Sorptivity (mm/√min)	Sulfate Resist. (% loss)	CO_2 Emiss. (kg/m³)
M0	5.82	3812	12.4	0.184	4.21	348.0
M1 (10%)	5.41	3204	11.1	0.161	3.74	314.4
M2 (20%)	4.87	2486	9.8	0.139	3.12	278.4
M3 (30%)	4.23	1842	8.3	0.118	2.61	243.6
M4 (40%)	3.91	1238	7.1	0.097	2.18	208.8
M5 (50%)	3.64	982	6.2	0.081	1.84	174.0

Table 5 shows that the introduction of fly ash most clearly bolsters arguments of sustainability benefits. The chloride ion penetrability RCPT value) drastically drops from 3812 Coulombs in M0 (classified as High permeability per ASTM C1202) to 1842 C in M3 (30% FA, classified as Low), and 982 C in M5(IV, classified as Very Low) The improved portion manifests the pores refinement as coarse capillary channels are filled with pozzolanic reaction products. Water absorption is recorded at 5.82% (M0) and falls to 3.64% (M5); sorptivity drops from 0.184 to 0.081 mm/√min, both indicating denser, less permeable microstructure. Decreasing depth of carbonation with increasing FA also contradicts the widespread misconception that FA concrete is more prone to carbonation, being attributed to the dominance of densified pore structure effects in lowering CO_2 diffusivity over limited availability of calcium hydroxide reservoir for carbonation. The decrease of 348.0 to 174.0 kg/m ³ confirms that replacing FA, in any level, provides direct environmental dividends 30% replacement renders the 30% emissions reduction, while 50% replacement renders a 50% reduction.

5. RESULTS AND DISCUSSION

5.1 STATISTICAL ANALYSIS

The results of the experiments were analyzed statistically with the objective of determining whether the replacement level of FA has a statistically significant impact on the properties of the concrete measured in this study. We used descriptive statistics, one-way ANOVA and Pearson correlation to characterize patterns, test hypotheses, and quantify the interrelationships between variables.

Table 6: Descriptive Statistics for Key Mechanical and Durability Parameters Across All Mixes

Parameter	Mean (MPa)	SD	CV (%)	Min	Max
28-day CS (all mixes)	33.43	5.28	15.8	24.5	38.2
90-day CS (all mixes)	41.88	3.62	8.64	34.7	45.6
Split Tensile Str.	2.94	0.29	9.86	2.41	3.21
Flexural Strength	4.46	0.41	9.19	3.74	4.85
Cl^- Penetration (C)	2260.7	1031	45.6	982	3812

From all six mixes, Table 6 provides descriptive statistics. The 28-day compressive strength is 33.43 MPa-5.28 MPa-15.8% (CV) which shows wide range (expected variation) among replacement levels. The 90-day compressive strength has a lower CV (8.64%), suggesting parsimony in late-age performance across mixes, a statistical equivalent of the pozzolanic catch-up effect. The split tensile strength (CV = 9.86%) and flexural strength (CV = 9.19%) have a moderate dispersion (i.e. a sign of good laboratory control). The chloride permeability (RCPT) has the highest CV (45.6%), indicating the high sensitivity of this durability parameter to the FA content. The results also indicate that for the three categories (High to Very Low) of permeability of concrete, based on the test values (982 C (M5) to 3812 C (M0)) measured, of three ASTM C1202 categories, once again demonstrating the far-reaching significance of the FA content selection for concrete long-term durability class.

Table 7: Two-Way ANOVA Results Effect of FA Replacement Level and Curing Age on Compressive Strength

Source of Variation	SS	df	MS	F-value	p-value	Sig.
FA Replacement Level (Between Groups)	1284.6	5	256.9	48.72	<0.001	***
Curing Age (Between Groups)	892.4	2	446.2	84.61	<0.001	***
Interaction (FA × Curing Age)	412.8	10	41.3	7.83	<0.001	***
Within Groups (Error)	189.3	36	5.26	—	—	—
Total	2779.1	53	—	—	—	—

Table 7 shows the (2-way ANOVA) results for FA replacement level (6 levels) and curing age (7, 28 and 90 days) on compressive strength with 3 replicates per cell (n = 54 observations). Both main effects are highly significant (FA replacement level: $F = 48.72$, $p < 0.001$; curing age: $F = 84.61$, $p < 0.001$; *, 0.1% level). Importantly, also notable is the interaction term (FA × Curing Age), which is highly significant ($F = 7.83$, $p < 0.001$), confirming that the effect of FA replacement on strength is non-constant with curing age the strength deficit is decreased at early ages and reversed at 90 days for low-to-moderate levels of FA. This statistically validated interaction is mechanistically at the core of the recommendation for FA concrete: the full curing duration has to be applied rather than the simplistic evaluation based on 28-day strength which constitutes the present state-of-the-practice in most Indian specification frameworks.

Table 8: Pearson Correlation Matrix Relationships Between FA Content, Strength, Durability, and CO_2 Emissions

Parameter	FA %	CS-28d	CS-90d	Cl^- Pen.	Slump	CO_2	Abs. %
FA %	1.000	−0.974**	−0.812**	−0.993**	0.997**	−1.000**	−0.991**
CS-28d	−0.974**	1.000	0.778*	0.968**	−0.969**	0.974**	0.976**
CS-90d	−0.812**	0.778*	1.000	0.824**	−0.826**	0.812**	0.803**
Cl^- Pen.	−0.993**	0.968**	0.824**	1.000	−0.991**	0.993**	0.987**
Slump	0.997**	−0.969**	−0.826**	−0.991**	1.000	−0.997**	−0.988**
CO_2	−1.000**	0.974**	0.812**	0.993**	−0.997**	1.000	0.991**
Abs. %	−0.991**	0.976**	0.803**	0.987**	−0.988**	0.991**	1.000

In Table 8, we show the Pearson correlation matrix with seven selected variables. The relationship between FA percentage and 28-day compressive strength is almost perfectly proportional but inversely ($r = -0.974$, $p < 0.01$), indicating that there exists a strong linear inverse relationship between FA content and short-term strength. The relationship with 90-day strength is weaker (r=−0.812), in accordance with the pozzolanic catch-up in hypethermal experiment. The FA content shows a near-perfect negative correlation with chloride penetration (r = −0.993), water absorption (r = −0.991), and CO_2 emissions (r = −1.000), and a near-perfect positive correlation with slump (r = 0.997). As a known linear relationship, the perfect negative correlation between FA% and CO_2 (r = −1.000) was anticipated due to the linear relationship between binder proportion and emission factor. Obsesrvations on concrete prepared with increasing levels of FA replacement reveal a strong (r = −0.969) negative correlation between 28-day compressive strength and slump, confirming the classical workability–strength trade-off and suggesting that workability-gains attained via reduced water–binder after titrations of FA cannot be achieved without attendant reductions in strength. The results offer strong statistical grounds for predictive models where FA replacement level is associated with performance and sustainability metrics.

5.2 CRITICAL ANALYSIS AND COMPARISON WITH PAST WORK

The 28-day compressive strength results obtained in the present study were similar to those reported by Siddique (2004) [8] (15–25% FA replacement for M25 concrete strength 35.8–37.2 MPa, 36.4–37.6 MPa compressive strength for present M1–M2 mixes). The primary 90-day performance advantage of moderate FA blends over an OPC control on this occasion, is consistent with a 90-day comparative investigation by Bilodeau and Malhotra (2000) [15] on high volume fly ash (HVFA [16 greenfield blog post]). The M5 (50% FA) results obtained in the present study is only 34.7 MPa at 90 days comparing to 40–50 MPa reported by Bilodeau and Malhotra, which is possibly related to the need of chemical admixtures combination in HVFA concrete as superplasticizer was omitted in the present mixes. Reduction in chloride penetrability, as observed during the present study (3812 C (M0) → 1842 C (M3)) is similar to previous work that examined a 30% FA replacement by Kumar and Singh (2010) [11] who reported RCPT values of 1680–2100 C, and a microstructural basis [9] (Mehta and Monteiro 2006). The 50% CO_2 reduction at 50% FA replacement is in line with Habert et al. When compared to the results of process-based LCA completed by Kuipers et al. (2011b) [17] for the previous studies showed that GWP reductions of over 40-50% when using a high replacement level of FA, this simplified emission factor approach can be supported [23].

The present study differs from previous work based on the explicit notion of barriers quantified alongside performance data. Previous studies by Pandey and Sharma (2000) [12] reported differences in the quality of ash but this result was not included into the estimates of the performance. The within-batch CV values for the present study (Table 6) represent controlled laboratory conditions with a single, pre-characterized ash source; field conditions with mixed sources of ash would produce CV values upwards of 2–3× greater, widening uncertainty bands around performance further [20]. All durability parameters are observed to increase monotonically with increasing FA content, while mechanical strength reaches a peak at 20–30% replacement at 90 days from a critical analysis of the correlation data (Table 8). This poses a fundamental optimization problem: the replacement level that minimizes durability (50%) is different than the replacement level that optimizes structural strength (20%) or environmental performance per unit strength (30%). There is no single ideal replacement level of FA, which necessitates exposure-class- and application-specific specification frameworks, an aspect of sophistication that is not achieved with the current information contained within IS: 456–2000 or IS: 10262–2019 since guidelines provided for SCM usage are very generic. In addition, the statistically significant interaction between FA replacement level and curing age (see Table 7) suggests that the conventional 28-day testing frameworks provide systematic biases against longer-term performance of FA concrete, predisposing it to structural biases in quality control frameworks based on 28-day cube crushing strength alone as the acceptance condition.

6. CONCLUSION

This empirical study presents statistically significant evidence that fly ash in concrete achieves tangible and substantial advantages in mechanical properties, durability and environmental sustainability efficiency. The main findings are: (i) replacement of FA at 20–30% achieves 90-day compressive strengths that are equal to or greater than those of OPC control, while lower CO_2 emissions by 20–30%; (ii) durability parameters related to chloride permeability (ASTM C1202), water absorption, and carbonation depth improve monotonically with increase in FA content, while 30% replacement shifts the concrete from 'High' permeability to 'Low' permeability class; (iii) a significant increase in workability with increase in FA significantly reduces the water to binder ratio in practice; (iv) two-way ANOVA interaction between FA level and curing age ($F = 7.83$, $p < 0.001$) confirms that 28-day-only evaluation systematically undervalues FA concrete; and (v) plastic CO_2 emissions decrease linearly with FA content reaching a 50% emission reduction at 50% replacement. Even though efforts must be made to overcome the barriers hindering FA adoption (e.g., early-age strength deficiency, heterogeneity of FA quality based on its source, conservatism of regulators and limited awareness of practitioners), they can become surmountable by the revised specification frameworks that.

7. REFERENCES

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