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Influence of Supplementary Cementitious Materials on the Strength and Selected Durability Parameters of Concrete a Comparative Study of 41 Mixtures

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Abstract

Conventional concrete specification relies heavily on compressive strength, water-to-binder ratio, minimum cement content, and nominal cover, none of which directly measures the resistance of hardened concrete to chloride ingress, gas penetration, or capillary water absorption. This study reports a comparative experimental investigation of 41 concrete mixtures incorporating Ordinary Portland Cement (OPC), two sources of Ground Granulated Blast-furnace Slag (Slag), Class F fly ash, and Class C fly ash at replacement levels of 15–70%, together with binary and ternary combinations, across water-to-binder ratios of 0.35–0.50 and binder contents of 350–450 kg/m³. Compressive strength, surface electrical resistivity, rapid chloride penetration (RCPT) charge, oxygen permeability index (OPI), and water sorptivity were measured at 28 and 90 days. Mean compressive strength increased by 16.7% between 28 and 90 days, mean surface resistivity increased by 79.9%, and mean RCPT charge decreased by 27.9%. Surface resistivity and RCPT charge were strongly and inversely correlated at both ages ($r = -0.704$ at 28 days; $r = -0.725$ at 90 days), whereas compressive strength showed only a weak association with RCPT ($r = -0.258$) and an essentially negligible association with resistivity ($r = +0.008$) at 90 days. In a controlled comparison at w/b = 0.50 and 310 kg/m³ binder content, a 50% slag mixture achieved the most balanced performance, exceeding the OPC control in strength (59.23 vs. 54.62 MPa) while improving resistivity by 7.38×, RCPT resistance by 6.40×, and sorptivity resistance by 3.03×. A 50% Class F fly ash mixture achieved comparable or superior chloride-related resistance (RCPT resistance 7.17×) but at a substantial strength penalty (0.57× the OPC strength). The results demonstrate that compressive strength alone cannot rank the durability performance of SCM concretes, and that a multi-parameter, exposure-specific assessment framework combining resistivity, RCPT, OPI, and sorptivity is required for dependable material selection.

Keywords: ***Supplementary cementitious materials; Concrete durability; Surface electrical resistivity; Rapid chloride penetration; Oxygen permeability index; Water sorptivity; Correlation analysis***.

I. INTRODUCTION

1.1 Background

Concrete durability is the ability of the material to sustain its required structural and serviceability performance under the physical, chemical, and environmental actions anticipated during its service life. Durability is governed by mixture composition, constituent-material quality, water-to-binder ratio, curing, cracking, and the severity of environmental exposure, with the near-surface concrete acting as the principal barrier against the ingress of aggressive substances. Corrosion of embedded reinforcement remains one of the leading causes of premature deterioration in reinforced concrete: the highly alkaline pore solution of sound concrete maintains a passive protective film on the steel, and this protection is disrupted either by the arrival of a critical chloride concentration at the bar or by a reduction in alkalinity caused by carbonation, both of which can initiate corrosion, expansive cracking, delamination, and spalling.

Supplementary Cementitious Materials (SCMs) principally fly ash and Ground Granulated Blast-furnace Slag (GGBS) are increasingly used as partial Portland cement replacements. Their pozzolanic or latent hydraulic reactions can generate additional binding phases, refine the pore structure, reduce pore connectivity, and modify pore-solution chemistry, generally improving resistance to chloride-related ionic transport and gas or water movement through the concrete. This benefit is exposure-dependent, however: while continued SCM reaction densifies the matrix, cement replacement and the associated consumption of calcium hydroxide reduce the alkaline reserve available to buffer incoming carbon dioxide, so a mixture offering excellent chloride resistance need not offer an equivalent improvement against carbonation.

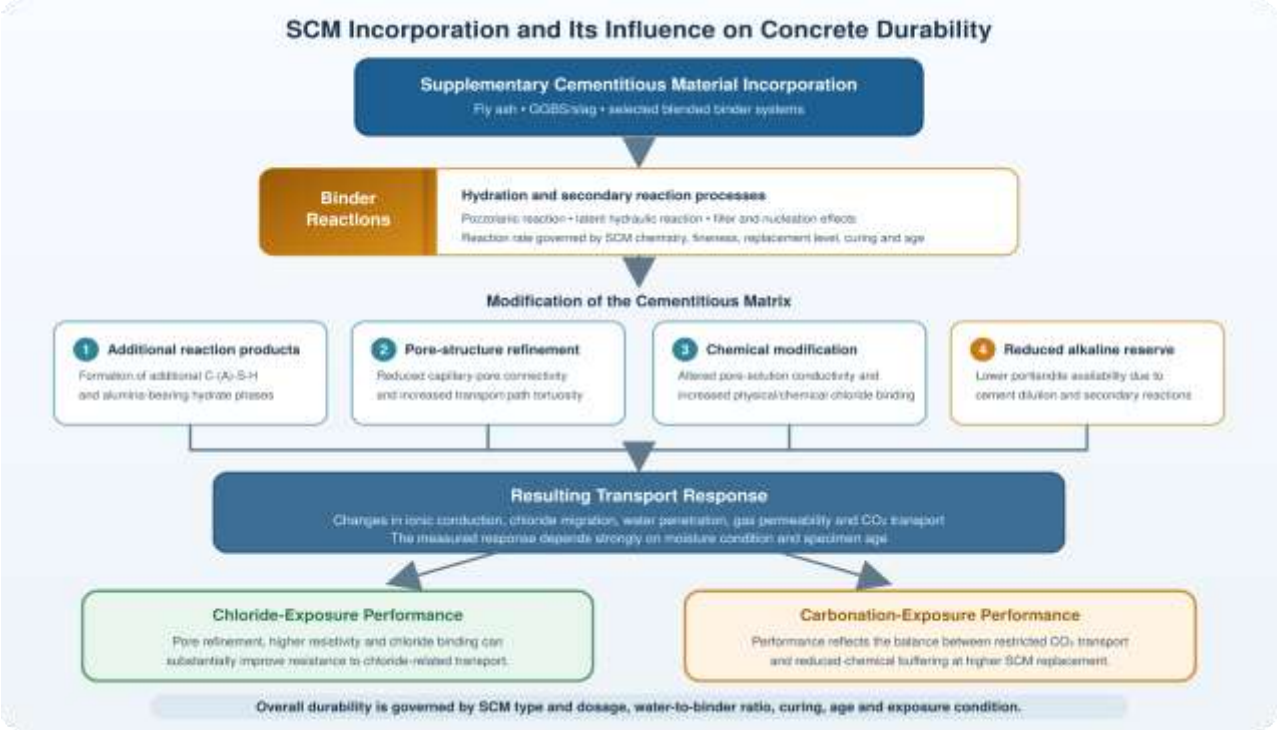


Fig-1: Conceptual relationship between SCM incorporation, binder reactions

1.2 Problem Statement

Conventional specification requirements characteristic compressive strength, maximum water-to-cement ratio, minimum cement content, and nominal cover contribute to concrete quality but do not directly measure resistance to chloride ingress, carbonation, gas transport, or water penetration. Mixtures satisfying an identical strength requirement can possess substantially different durability characteristics because of differences in binder composition, SCM replacement level, curing response, pore structure, and pore-solution chemistry. This limitation is

compounded because different durability tests represent different transport or deterioration mechanisms: electrical resistivity indicates resistance to ionic conduction, RCPT represents electrically assisted ionic movement, gas permeability reflects the continuity of gas-filled transport paths, and water-based tests represent capillary absorption or pressure-driven permeation. A single test result is therefore an incomplete basis for durability assessment, and the relationships among these parameters must be established before any one of them is treated as a substitute for another.

1.3 Aim and Objectives

The aim of this study is to evaluate the influence of SCMs on selected mechanical and durability characteristics of concrete and to develop a practical, multi-parameter framework for comparing SCM-based concretes. The specific objectives are to:

(i) Develop a database of compressive strength and durability parameters for 41 concrete mixtures incorporating different SCM types and replacement levels;

(ii) Evaluate the influence of binder content, water-to-binder ratio, SCM type, replacement level, and curing age on mechanical and durability performance;

(iii) Assess resistance to chloride-related ionic transport, gas penetration, and water sorptivity;

(iv) Examine the statistical relationships among compressive strength, surface resistivity, RCPT charge, oxygen permeability index, and sorptivity; and

Develop a controlled, strength-normalized comparison of binder systems to support performance-based material selection.

1.4 Scope

The experimental programme covers 41 concrete mixtures produced with OPC, two slag sources, Class F fly ash, and Class C fly ash, varying binder content (350, 400, and 450 kg/m³), water-to-binder ratio (0.35–0.50), and SCM replacement level (15–70%, including binary and ternary blends). The verified numerical analysis reported here covers compressive strength, surface electrical resistivity, RCPT charge, oxygen permeability index, and water sorptivity at 28 and 90 days. Rapid chloride migration, chloride conductivity, Torrent air permeability, accelerated carbonation, pressure-water penetration, and microstructural (SEM/XRD/TGA) results were part of the broader experimental programme but are not included in the quantitative comparisons of this paper because complete, traceable numerical datasets across all 41 mixtures were not available; these are noted as directions for future reporting rather than included as unsupported figures.

II. RELATED WORK

The chemical mechanism of chloride resistance in SCM concrete has been examined extensively. Abd El-Fattah et al. [1] showed that GGBS and, to a lesser extent, metakaolin increase the chloride-binding capacity of concrete relative to an OPC control, with GGBS supplying both the calcium and alumina required to form Friedel's salt, confirmed by X-ray diffraction; they concluded that allowable chloride limits should reflect binder type rather than a single universal value. Wei et al. [4] similarly found that chloride binding depends on binder chemistry rather than fineness alone, and that excessive silica fume content can reduce chloride binding despite improving physical densification. Thomas et al. [7] demonstrated that both chemical binding (via alumina-bearing phases) and physical adsorption (via C-S-H) govern the partition between free and bound chloride, and cautioned against assuming identical behaviour for OPC and blended binders. Lollini et al. [8] extended this to corrosion initiation, showing that the critical chloride threshold of embedded steel is not a universal constant but varies with binder composition and pore-solution alkalinity.

The trade-off between chloride resistance and carbonation resistance in SCM concrete is well established. Papadakis [6] showed that SCM incorporation can substantially reduce chloride ingress through pore refinement while simultaneously increasing carbonation depth because cement replacement reduces the alkaline reserve available to neutralize incoming CO_2 a mixture may therefore be excellent against one deterioration mechanism and inferior against the other. Von Greve-Dierfeld et al. [5], in a RILEM TC 281-CCC review, confirmed that carbonation resistance in SCM concrete depends on a balance between improved transport resistance and reduced chemical buffering capacity, and that it cannot

be predicted from replacement percentage alone. Shah et al. [13] used detailed microstructural analysis to show that carbonation of blended binders differs from OPC because SCM reaction alters the calcium-to-silicon ratio and portlandite content of the paste.

A separate body of work addresses the interpretation and cross-validation of durability test methods. Ghosh and Tran [9] established a controllable relationship between bulk and surface electrical resistivity, provided specimen geometry, saturation, and temperature are standardized. Basheer et al. [11] reviewed permeation-based durability assessment and emphasized that permeability, absorption, and diffusion represent distinct transport processes that should not be reduced to a single generalized value gas-permeability results are highly sensitive to residual moisture, water absorption depends on capillary forces and initial moisture state, and electrical chloride tests depend additionally on pore-solution conductivity. Tang and Nilsson [14] developed the accelerated electrical-migration principle underlying RCPT-type testing, while noting that electrically driven migration differs from natural diffusion and is affected by voltage, temperature, and pore-solution composition. Torrent [15] developed an in-situ air-permeability method for the concrete cover and showed that poorly cured concrete can exhibit high permeability even at satisfactory compressive strength.

Broader syntheses converge on the same conclusion reached in this study. Alexander et al. [10] proposed a durability-index framework in which oxygen permeability, water sorptivity, and chloride-related conductivity are treated as complementary, non-substitutable indicators, having demonstrated that concretes of similar compressive strength can possess substantially different durability-index values. Shi et al. [12] reviewed chloride-induced deterioration of reinforced concrete and confirmed that SCMs reduce chloride penetration through both pore-network refinement and chloride binding, with the relative contribution depending on SCM type. Lothenbach et al. [16] and Scrivener et al. [17] provided the underlying microstructural and analytical basis for these transport changes, describing how SCM reaction consumes calcium hydroxide and forms additional binding phases that reduce pore connectivity. Mehta and Monteiro [18] and Neville [19] both emphasize, at a textbook level, that total porosity alone does not control durability pore connectivity, size distribution, and tortuosity are equally significant and that permeability cannot always be inferred from strength.

2.1 Research Gap

Most published investigations evaluate only one or two durability parameters and do not examine whether different indicators rank the same set of mixtures consistently. Published correlations between strength, resistivity, RCPT, and permeability are, moreover, strongly dependent on the specific materials and testing conditions used and cannot be transferred automatically to concrete produced with a different SCM source, binder content, water-to-binder ratio, or curing regime. A systematic, material-specific comparison across mixtures of similar compressive strength is particularly lacking, despite its direct relevance to performance-based specification. The present investigation addresses this gap through a controlled 41-mixture database spanning multiple SCM types, replacement levels, water-to-binder ratios, and binder contents, evaluated jointly across five complementary parameters at two curing ages.

III. MATERIALS AND METHODS

3.1 Materials

OPC 53 grade conforming to IS 12269 was used as the primary cementitious material. Class F fly ash conforming to IS 3812 (Part 1) was used as the pozzolanic component, and GGBS (from two slag sources) conforming to IS 16714 was used as the latent hydraulic component; a Class C fly ash was additionally included. All binders were stored in sealed, moisture-resistant containers and homogenized before batching. Natural river sand conforming to IS 383 was used as fine aggregate, and crushed angular stone of nominal 10 mm and 20 mm size (combined approximately 40:60 by mass) was used as coarse aggregate, with fine aggregate constituting approximately 38% of total aggregate volume. Potable water was used for mixing and curing, and a polycarboxylate-ether superplasticizer conforming to IS 9103 was used where necessary to maintain workability without altering the specified water-to-binder ratio.

3.2 Experimental Matrix and Mix Proportions

3.2 Experimental Matrix and Mix Proportions

The experimental programme comprised 41 concrete mixtures. The principal matrix contained 36 mixtures at a constant total binder content of 400 kg/m³, combining four water-to-binder ratios (0.35, 0.40, 0.45, 0.50) with nine binder systems: an OPC control, Class F fly ash at 20%, 35%, and 50% replacement, GGBS at 30%, 50%, and 70% replacement, and two ternary fly-ash–GGBS blends (15% FA + 15% GGBS; 20% FA + 30% GGBS). Five additional mixtures at binder contents of 350 or 450 kg/m³ (constant w/b = 0.40) were included to examine the influence of paste volume. Concrete was proportioned by the absolute-volume method; the mix code identifies the binder system and water-to-binder ratio (e.g., F35-40 denotes 35% fly-ash replacement at w/b = 0.40; G50-45 denotes 50% GGBS at w/b = 0.45). The complete mixture matrix is given in Table 1.

Table 1. Concrete mixture matrix binder and water content (kg/m³).

Mix code	Binder (kg/m³)	w/b	OPC (kg/m³)	Fly ash (kg/m³)	GGBS (kg/m³)	Water (kg/m³)
C35	400	0.35	400	0	0	140
C40	400	0.40	400	0	0	160
C45	400	0.45	400	0	0	180
C50	400	0.50	400	0	0	200
F20-35	400	0.35	320	80	0	140
F20-40	400	0.40	320	80	0	160
F20-45	400	0.45	320	80	0	180
F20-50	400	0.50	320	80	0	200
F35-35	400	0.35	260	140	0	140
F35-40	400	0.40	260	140	0	160

Mix code	Binder (kg/m³)	w/b	OPC (kg/m³)	Fly ash (kg/m³)	GGBS (kg/m³)	Water (kg/m³)
F35-45	400	0.45	260	140	0	180
F35-50	400	0.50	260	140	0	200
F50-35	400	0.35	200	200	0	140
F50-40	400	0.40	200	200	0	160
F50-45	400	0.45	200	200	0	180
F50-50	400	0.50	200	200	0	200
G30-35	400	0.35	280	0	120	140
G30-40	400	0.40	280	0	120	160
G30-45	400	0.45	280	0	120	180
G30-50	400	0.50	280	0	120	200
G50-35	400	0.35	200	0	200	140
G50-40	400	0.40	200	0	200	160
G50-45	400	0.45	200	0	200	180
G50-50	400	0.50	200	0	200	200
G70-35	400	0.35	120	0	280	140
G70-40	400	0.40	120	0	280	160
G70-45	400	0.45	120	0	280	180
G70-50	400	0.50	120	0	280	200
T30-35	400	0.35	280	60	60	140
T30-40	400	0.40	280	60	60	160
T30-45	400	0.45	280	60	60	180
T30-50	400	0.50	280	60	60	200
T50-35	400	0.35	200	80	120	140

Mix code	Binder (kg/m³)	w/b	OPC (kg/m³)	Fly ash (kg/m³)	GGBS (kg/m³)	Water (kg/m³)
T50-40	400	0.40	200	80	120	160
T50-45	400	0.45	200	80	120	180
T50-50	400	0.50	200	80	120	200
C350-40	350	0.40	350	0	0	140
C450-40	450	0.40	450	0	0	180
F35-350-40	350	0.40	227.5	122.5	0	140
F35-450-40	450	0.40	292.5	157.5	0	180
G50-450-40	450	0.40	225	0	225	180

Unless stated otherwise, three specimens were tested per reported condition and the arithmetic mean reported as the representative result. Aggregate moisture content was checked and corrected on each casting day, and superplasticizer dosage was set to achieve a target slump of 75–100 mm.

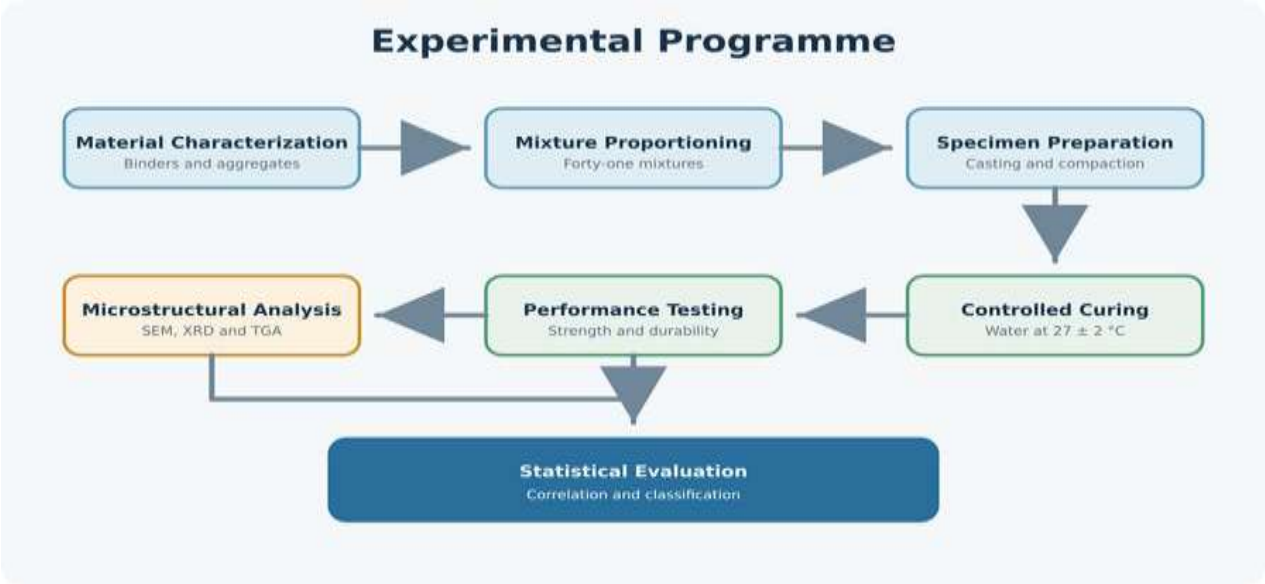


Fig-2: Experimental programme Sequence

3.3 Specimen Preparation and Curing

Fine and coarse aggregates were dry-mixed for approximately 1 minute before OPC, fly ash, and GGBS were added and mixed to uniform distribution. Approximately 70% of the corrected mixing water was added gradually; the remaining 30% was combined with the required superplasticizer dose and added during final wet mixing, followed by 2 minutes of wet mixing, a 1-minute rest, and a further 1-minute mixing period. Slump and fresh-concrete temperature were recorded immediately after mixing. Specimens were cast in layers, compacted on a vibrating table, covered

for approximately 24 hours, demoulded, and then water-cured at 27 ± 2 °C until the relevant test age.

3.4 Test Methods

Compressive strength was determined on 100 mm cubes at 7, 28, 56, and 90 days as $f^c = P/A$, where P is the maximum applied load and A is the loaded area, with the mean of three cubes reported at each age. Surface electrical resistivity was measured on saturated-surface-dry 100 × 200 mm cylinders using a four-point Wenner probe, with four readings taken around the circumference (rotated approximately 90° between readings) and averaged, following the ASTM C1876 principle. Rapid chloride penetration followed the ASTM C1202 principle: vacuum-saturated 100 mm-diameter, 50 mm-thick discs were exposed to 3.0% NaCl on one face and 0.3 M NaOH on the opposite face under a 60 V potential for 6 hours, with current recorded at 30-minute intervals and total charge passed obtained by trapezoidal integration, $Q = 900(I_0 + 2I_{30} + 2I_{60} + \ldots + 2I_{330} + I_{360})$. Because SCMs alter pore-solution conductivity, charge passed was interpreted together with resistivity rather than as a direct diffusion coefficient. Gas permeability was assessed on conditioned 150 × 50 mm discs in a sealed steady-flow cell, from which the oxygen permeability index (OPI) was derived; residual moisture strongly affects this measurement, so conditioning history was controlled consistently. Water sorptivity was evaluated by capillary absorption testing following the ASTM C1585 principle, reported as a sorptivity index in mm/√hr.

IV. RESULTS AND DISCUSSION

4.1 Data Coverage

The verified numerical analysis covers 41 concrete mixtures at 28 and 90 days for compressive strength, surface resistivity, RCPT charge, and sorptivity (n = 41 at each age), and 37 mixtures for OPI. Table 2 summarizes the range and mean of each parameter across the full database. Recorded fresh-concrete properties across the 41 mixtures indicate a broad but workable consistency range: ambient temperature 28–36 °C, slump 70–150 mm (mean 97.1 mm), unit weight 2371–2498 kg/m³, and air content 0.8–2.5%.

Table 2. Measured-result coverage and range across the 41-mixture database

Parameter	Age (days)	n	Minimum	Maximum	Mean	Unit
Compressive strength	28	41	21.27	70.48	42.83	MPa
Compressive strength	90	41	27.81	82.95	49.99	MPa
Surface resistivity	28	41	8.19	84.75	19.01	kΩ·cm
Surface resistivity	90	41	9.08	120.00	34.21	kΩ·cm
RCPT charge	28	41	390	4465	2262	C
RCPT charge	90	41	250	4030	1631	C
Oxygen permeability index	28	37	9.76	10.79	10.17	–
Oxygen permeability index	90	37	9.66	11.00	10.23	–
Sorptivity index	28	41	2.93	13.11	8.16	mm/√hr

Parameter	Age (days)	n	Minimum	Maximum	Mean	Unit
Sorptivity index	90	41	4.76	14.43	8.92	mm/√hr

4.2 Compressive Strength Development

Every mixture recorded higher compressive strength at 90 days than at 28 days except three mixtures that showed a marginal reduction; across the database, mean compressive strength increased from 42.83 to 49.99 MPa (+16.7%). Within the controlled w/b = 0.50, 310 kg/m³ comparison series, 50% slag (S50) reached 59.23 MPa at 90 days, exceeding the 54.62 MPa OPC control, whereas Class F fly ash showed a clear replacement-level penalty: 49.96 MPa at 15% replacement (F15), 39.77 MPa at 30% (F30), and 31.33 MPa at 50% (F50). The chloride-related benefit of high fly-ash replacement (Section 4.3) must therefore be weighed against this strength-development penalty.

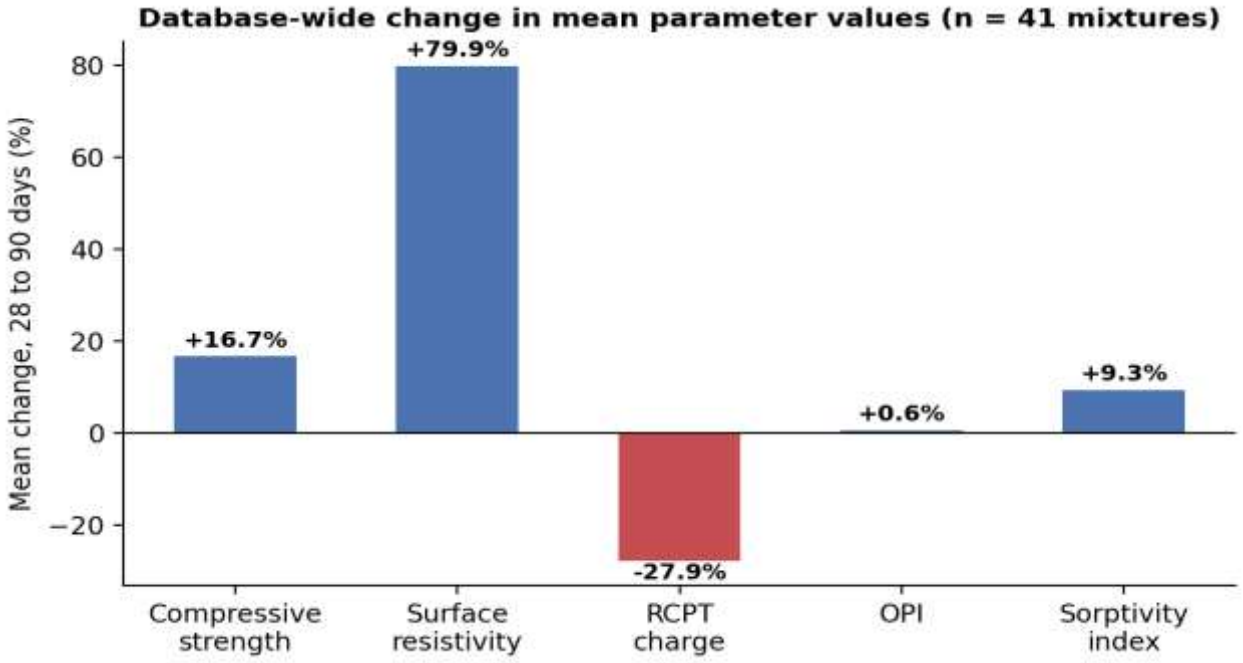


Fig. 1. Database-wide mean change in each measured parameter between 28 and 90 days (n = 41; OPI n = 37).

4.3 Chloride-Related Performance

Mean surface resistivity increased from 19.01 to 34.21 kΩ·cm (+79.9%) between 28 and 90 days, with all 41 mixtures showing an increase — the most consistent age-related trend of any parameter measured, reflecting continued reaction and refinement of the conductive pore network. In the controlled comparison series, S50 and F50 reached 120.00 and 110.00 kΩ·cm at 90 days respectively, compared with 16.25 kΩ·cm for OPC; Class C fly ash produced a more moderate increase than Class F fly ash or slag at comparable replacement levels (Table 3, Fig. 2).

Mean RCPT charge decreased from 2262 C to 1631 C (−27.9%), with 40 of 41 mixtures showing a reduction. In the controlled series, OPC recorded 2080 C at 90 days while S50 and F50 recorded 325 C and 290 C respectively — an order-of-magnitude reduction. The age-related improvement was particularly pronounced for Class F fly ash: the F50 mixture fell from 720 C at 28 days to 290 C at 90 days despite retaining lower compressive strength than the OPC control throughout (Table 3, Fig. 3).

Table 3. Selected 90-day measured results across binder systems (w/b = 0.50, 310 kg/m³ binder).

Binder	Mix ID	Strength (MPa)	Resistivity (kΩ·cm)	RCPT (C)	OPI (–)	Sorptivity (mm/√hr)
OPC	LFM5	54.62	16.25	2080	10.09	14.43
S15	LFM22	47.55	26.67	2100	10.01	10.10
S30	LFM23	52.06	39.17	1075	10.75	9.40
S50	LFM24	59.23	120.00	325	10.81	4.76
F15	LFM33	49.96	37.83	995	10.06	8.61
F30	LFM34	39.77	68.67	980	10.73	6.79
F50	LFM35	31.33	110.00	290	10.03	12.54
C15	LFM43	44.12	17.83	2005	10.46	7.97
C30	LFM44	44.22	23.75	1280	10.21	6.94

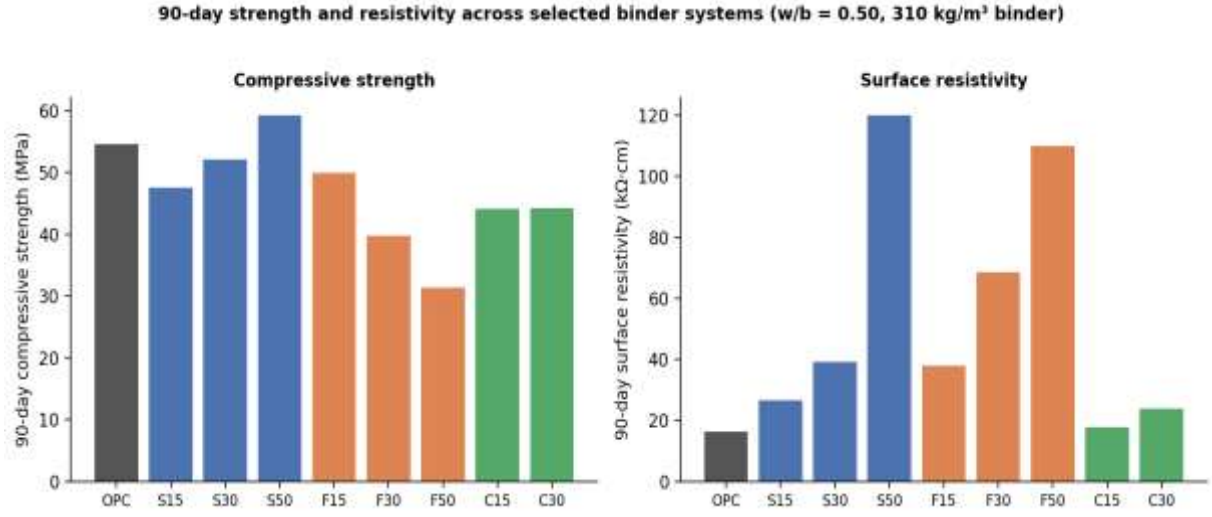


Fig. 2. 90-day compressive strength and surface resistivity across selected binder systems.

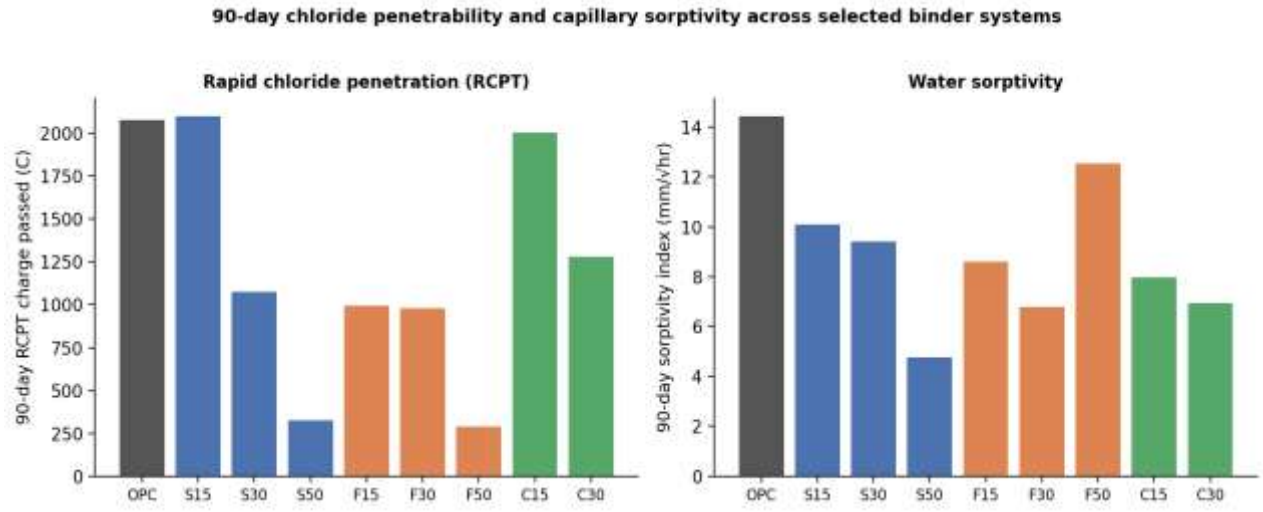


Fig. 3. 90-day RCPT charge and sorptivity index across selected binder systems.

Surface resistivity and RCPT charge were strongly and inversely correlated at both ages (r = −0.704 at 28 days; r = −0.725 at 90 days), supporting the use of surface resistivity as a rapid, non-destructive comparative indicator of chloride-related transport within this material set, provided moisture condition and temperature are controlled

4.4 Gas Penetrability (OPI)

OPI values occupied a comparatively narrow range — 9.76–10.79 at 28 days and 9.66–11.00 at 90 days — with the database mean essentially unchanged (10.17 to 10.23, +0.6%). In the controlled series, S50 produced the highest 90-day OPI (10.81) against 10.09 for OPC, a modest difference relative to the order-of-magnitude changes seen in resistivity and RCPT. OPI should therefore be retained where gas penetrability is the governing exposure mechanism but should not be treated as a direct substitute for chloride-related measurements.

4.5 Water Sorptivity

Sorptivity ranged from 2.93–13.11 mm/√hr at 28 days to 4.76–14.43 mm/√hr at 90 days, with the database mean increasing slightly (8.16 to 8.92 mm/√hr, +9.3%) — 22 mixtures increased and 19 decreased, so no uniform age-related trend was observed and mixture-specific comparison is more informative than the overall mean. In the controlled series, S50 recorded the lowest 90-day sorptivity (4.76 mm/√hr) against 14.43 mm/√hr for OPC, while F50 retained a comparatively high sorptivity (12.54 mm/√hr) despite its excellent RCPT and resistivity performance — direct evidence that different transport tests need not rank mixtures identically.

4.6 Correlation Analysis

Table 4 and Fig. 4 present the 90-day Pearson correlation matrix among the five retained parameters. Compressive strength was essentially uncorrelated with surface resistivity (r = +0.008) and only weakly correlated with RCPT charge (r = −0.258) at 90 days, confirming that compressive strength alone cannot rank durability-related performance among concretes containing different SCMs. Surface resistivity and RCPT remained the strongest pair (r = −0.725), while OPI showed moderate associations with RCPT (r = −0.512) and sorptivity (r = −0.540). Sorptivity and RCPT showed a moderate positive association (r = +0.460). These moderate-strength associations are meaningful but not strong enough to treat the corresponding tests as interchangeable.

Table 4. Principal parameter correlations at 28 and 90 days.

Parameter pair	Age	n	r	R^2	Magnitude
Strength–resistivity	28	41	0.083	0.007	Weak
Strength–resistivity	90	41	0.008	0.000	Weak
Strength–RCPT	28	41	-0.198	0.039	Weak
Strength–RCPT	90	41	-0.258	0.067	Weak
Resistivity–RCPT	28	41	-0.704	0.496	Strong
Resistivity–RCPT	90	41	-0.725	0.526	Strong
OPI–RCPT	28	37	-0.334	0.112	Moderate
OPI–RCPT	90	37	-0.512	0.262	Moderate
Sorptivity–RCPT	28	41	0.195	0.038	Weak
Sorptivity–RCPT	90	41	0.460	0.212	Moderate
OPI–sorptivity	28	37	-0.072	0.005	Weak
OPI–sorptivity	90	37	-0.540	0.291	Moderate

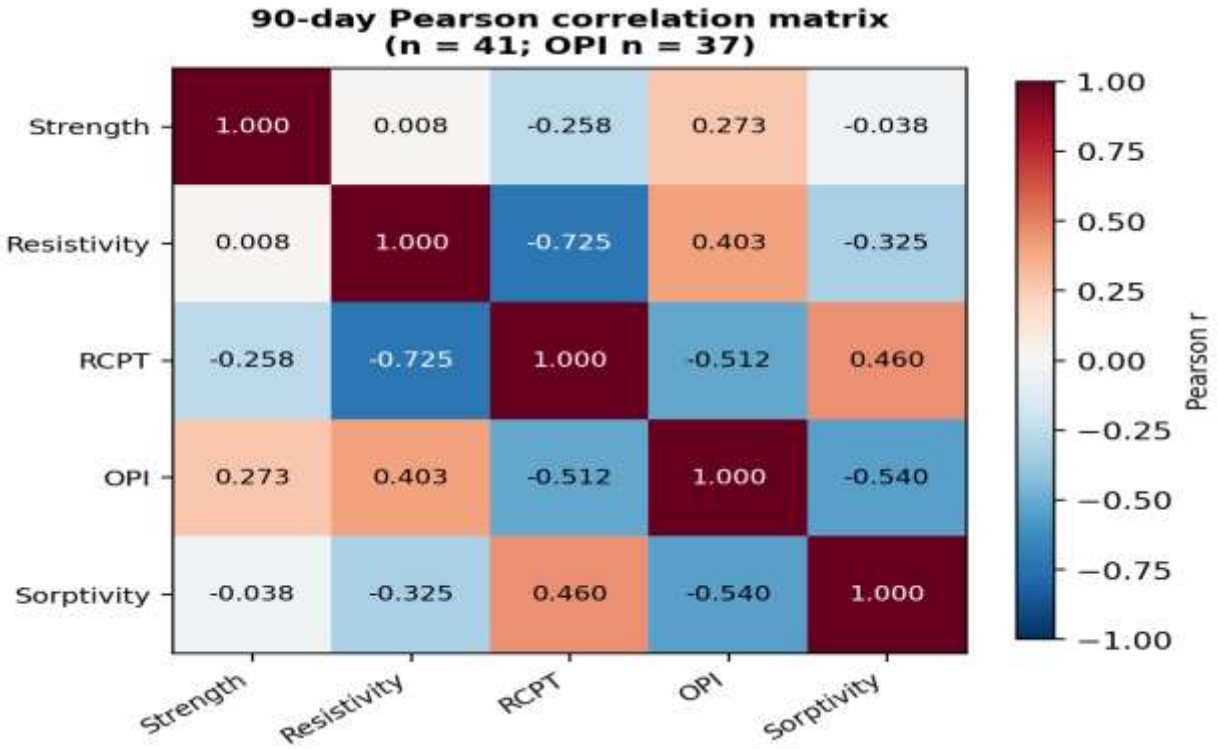


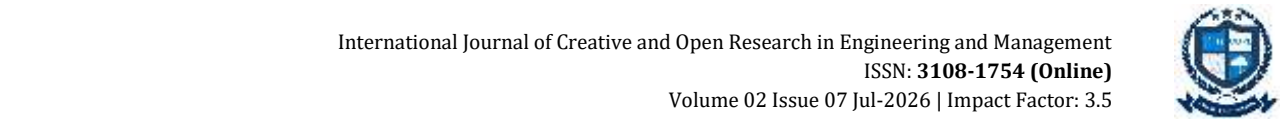
Fig. 4. 90-day Pearson correlation matrix among the five retained durability and strength parameters (n = 41; OPI n = 37).

4.7 Controlled Binder Comparison

Table 5 and Fig. 5 present 90-day performance normalized to the OPC control within the w/b = 0.50, 310 kg/m³ comparison series (values above 1.0 indicate improvement over OPC in all cases, with RCPT and sorptivity inverted to represent resistance). S50 provided the most balanced response: 1.08× the OPC strength, 7.38× the resistivity, 6.40× the RCPT resistance, 1.07× the OPI, and 3.03× the sorptivity resistance — the only binder system to simultaneously exceed OPC in every parameter measured. F50 achieved the highest RCPT resistance (7.17×) but at only 0.57× the OPC strength, illustrating the trade-off between chloride-related resistance and mechanical capacity at high fly-ash replacement.

Table 5. 90-day performance ratios relative to the OPC control (w/b = 0.50, 310 kg/m³ binder).

Binder	Strength	Resistivity	RCPT resistance	OPI	Sorptivity resistance
OPC	1.00×	1.00×	1.00×	1.00×	1.00×
S15	0.87×	1.64×	0.99×	0.99×	1.43×
S30	0.95×	2.41×	1.93×	1.07×	1.54×
S50	1.08×	7.38×	6.40×	1.07×	3.03×
F15	0.91×	2.33×	2.09×	1.00×	1.68×
F30	0.73×	4.23×	2.12×	1.06×	2.13×
F50	0.57×	6.77×	7.17×	0.99×	1.15×



Binder	Strength	Resistivity	RCPT resistance	OPI	Sorptivity resistance
C15	0.81×	1.10×	1.04×	1.04×	1.81×
C30	0.81×	1.46×	1.62×	1.01×	2.08×

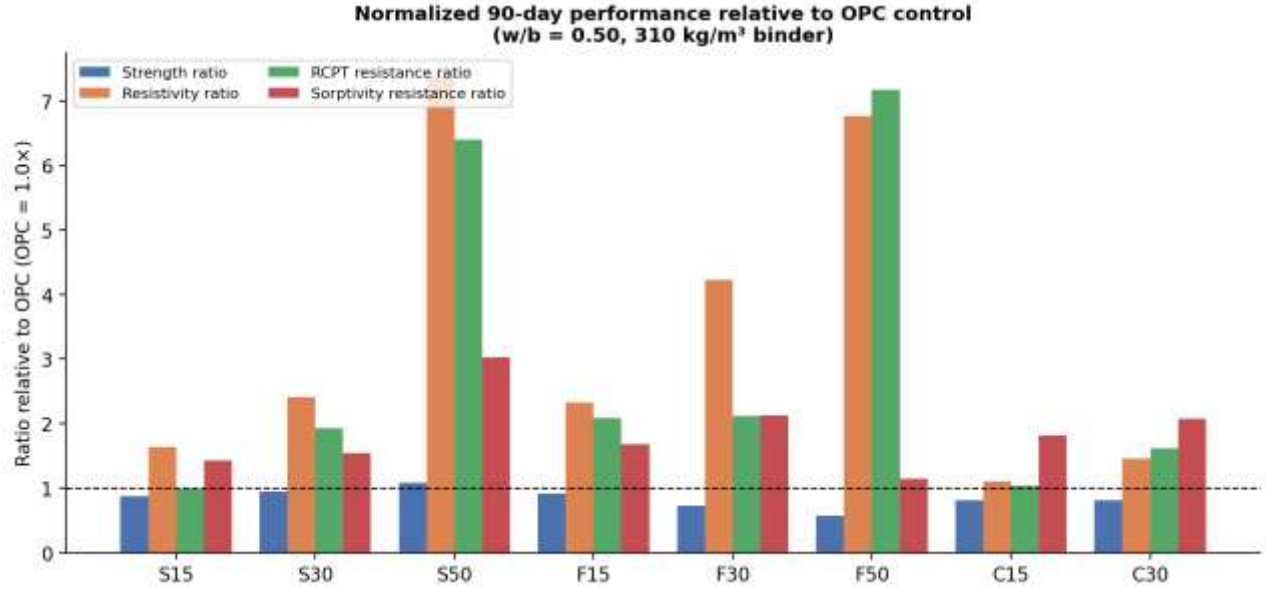


Fig. 5. Normalized 90-day performance of each binder system relative to the OPC control.

4.8 Durability Variability within Strength Bands

To examine whether comparable compressive strength implies comparable durability, the 28-day strengths of all 41 mixtures were grouped into five analytical bands (Table 6); these bands are used solely for within-band comparison and are not structural concrete grades. RCPT charge retained a wide spread within every band — for example, mixtures in the 40–<50 MPa band ranged from 1105 to 4465 C, a four-fold spread despite comparable strength — confirming that compressive strength does not ensure comparable chloride-related performance and reinforcing the need for independent durability assessment.

Table 6. Durability spread within 28-day compressive-strength bands.

Band (MPa)	n	Strength range (MPa)	Resistivity range (kΩ·cm)	RCPT range (C)
<30	5	21.27–29.90	8.88–46.92	720–3285
30–<40	12	31.71–39.90	9.02–30.25	1000–4030
40–<50	16	40.01–49.15	8.19–32.92	1105–4465
50–<60	5	50.41–59.08	10.17–84.75	390–4200
≥60	3	65.74–70.48	14.75–23.83	975–1515

4.9 Engineering Interpretation

The combined evidence supports a performance-based, multi-parameter approach to SCM concrete selection rather than reliance on compressive strength or any single durability indicator. Compressive strength should be used to confirm mechanical adequacy; surface resistivity, given its strong correlation with RCPT and its simple, non-destructive measurement, is well suited to rapid chloride-related screening, with RCPT retained as a complementary electrical-transport measurement; sorptivity should be assessed directly wherever capillary water uptake is the governing exposure mechanism, since its mixture ranking did not reproduce the electrical chloride ranking; and OPI should be retained where gas penetrability is relevant, notwithstanding its narrower discriminating range in this dataset. No mixture in the investigated set can be described as universally durable: the appropriate binder system depends on the required strength grade, curing duration, and the dominant deterioration mechanism of the intended exposure environment.

V. CONCLUSION

Based on the comparative evaluation of 41 concrete mixtures incorporating OPC, slag, and Class F and Class C fly ash, the following conclusions are drawn:

1. Later-age development was evident but parameter-dependent: mean compressive strength increased by 16.7% and mean surface resistivity by 79.9% between 28 and 90 days, while mean RCPT charge decreased by 27.9%; all three trends are consistent with continued SCM reaction, but sorptivity and OPI did not follow a uniform age-related pattern.

2. Surface resistivity and RCPT charge were strongly and consistently inversely correlated ($r = -0.70$ to -0.73 at both ages), supporting resistivity as a rapid, non-destructive comparative indicator of chloride-related transport within the investigated material set.

3. Compressive strength could not independently represent durability performance: at 90 days the strength–RCPT correlation was weak ($r = -0.258$) and the strength–resistivity correlation was effectively absent ($r = +0.008$), so mixtures of comparable strength can possess markedly different chloride-related transport characteristics — confirmed directly by the four-fold RCPT spread observed within a single 28-day strength band.

4. A 50% slag replacement (S50) produced the most balanced 90-day performance in the controlled comparison, simultaneously exceeding the OPC control in strength, resistivity, RCPT resistance, OPI, and sorptivity resistance.

5. A 50% Class F fly ash replacement (F50) achieved the strongest electrical chloride resistance of all mixtures tested (RCPT resistance 7.17× OPC) but at a substantial strength penalty (0.57× OPC strength), demonstrating that high chloride resistance and structural strength requirements must be reconciled through the choice of replacement level rather than assumed to coincide.

6. Sorptivity and OPI provided independent information not captured by resistivity or RCPT: the F50 mixture, despite near-best chloride-related performance, retained a comparatively high sorptivity, confirming that durability assessment should combine complementary parameters representing different transport mechanisms rather than rely on any single test.

These findings support a performance-based SCM concrete selection framework in which compressive strength confirms mechanical adequacy while resistivity, RCPT, OPI, and sorptivity are assessed jointly according to the governing exposure mechanism, rather than inferring durability from strength or replacement percentage alone.

5.1 Limitations and Future Work

The findings apply to the material sources, mixture ranges, curing conditions, and laboratory procedures used in this programme; the reported correlations describe statistical association within this dataset and do not establish causation or universal acceptance limits. RCPT and resistivity both depend partly on electrical conduction through the pore solution and are therefore not fully independent physical measures. Complete, traceable numerical datasets for rapid chloride migration, chloride conductivity, Torrent air permeability, accelerated carbonation, pressure-water penetration, and microstructural (SEM/XRD/TGA) measurements were part of the broader experimental programme but were not included in the present quantitative analysis; completing and indexing these datasets, extending testing to 180 and 365 days, and

validating laboratory trends against natural chloride and atmospheric exposure are recommended directions for future work. Laboratory results were not converted to a predicted field service life because exposure concentration, cover depth, construction variability, and a validated deterioration model were outside the scope of this study.

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