Development of High-Performance Multi-Blended Concrete for Enhanced Strength and Durability in Aggressive Environments

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***Abstract*—** Hydraulic and water-retaining concrete structures, including spillways, stilling basins, dam foundations, and diversion tunnels, frequently suffer premature structural degradation when exposed to aggressive service environments. Continuous high-velocity silt-laden water flow, chloride-induced reinforcement corrosion, and deleterious alkali-silica reaction (ASR) severely shorten the service life of conventional Ordinary Portland Cement (OPC) concrete. This paper presents an experimental investigation into the mechanical and durability behavior of high-performance multi-blended concrete (MBC) formulated by partially replacing OPC with Low-Calcium Class F Fly Ash (LCFA) and densified Silica Fume (SF). Twelve concrete mixtures were proportioned at a constant water-to-binder (w/b) ratio of 0.42 and a total binder content of 365 kg/m³, comprising a control M30 OPC mix, binary mixes incorporating LCFA (20%, 30%, and 40%) or SF (5% and 10%), and six ternary blends combining LCFA (20%–40%) with SF (5% and 10%). Fresh concrete workability was controlled within a 50–70 mm slump range using a polycarboxylic ether (PCE) superplasticizer. Hardened concrete specimens were evaluated for compressive strength at 7, 28, 56, and 91 days, non-destructive structural quality via Ultrasonic Pulse Velocity (UPV), and resistance to chloride ion ingress via the Rapid Chloride Permeability Test (RCPT). Experimental results indicate that while binary LCFA mixes experience reduced early-age strength, they achieve strength parity with control concrete at 91 days. Conversely, binary SF mixes accelerate early hydration, with CS10 reaching 34.26 MPa at 28 days and 39.68 MPa at 91 days. Among the ternary blends, the mixture combining 30% LCFA and 5% SF (CFS635) achieved the highest 91-day compressive strength of 41.50 MPa (an 8.13% gain over the control mix), alongside superior UPV ratings and markedly reduced chloride permeability. The findings confirm that balanced ternary binder combinations mitigate individual pozzolan limitations and provide a durable, sustainable solution for infrastructure operating in aggressive environments.

***Keywords*—** *Multi-blended concrete, supplementary cementitious materials, low-calcium fly ash, silica fume, compressive strength, ultrasonic pulse velocity, rapid chloride permeability, alkali-silica reaction, hydraulic structures.*

I. INTRODUCTION

Concrete infrastructure built for water resources and hydroelectric power generation—such as spillways, stilling basins, glacis slopes, energy dissipators, tunnel linings, and dam foundations—operates under severe mechanical and chemical exposure. Although properly designed concrete structures can maintain serviceability for over five decades, field inspections across major hydraulic installations reveal widespread premature deterioration within 25 to 35 years of commissioning [1], [2]. Primary degradation mechanisms include underwater abrasion-erosion caused by sediment-laden high-velocity flows, reinforcement corrosion triggered by chloride ion penetration, and internal cracking driven by alkali-silica reaction (ASR).

Field evidence from major hydraulic structures underscores the urgency of improving concrete durability. For example, the Rihand Dam and adjacent powerhouse experienced severe structural distress after 25 years due to ASR-induced expansion, resulting in pier cracking, gate-operation binding, and a 3 cm horizontal displacement between powerhouse crane girders [2]. Similarly, the Hirakud Dam spillway developed extensive gallery and shaft cracking after 27 years of service, leading to bolt failures on sluice gate guide rails. In high-abrasion zones such as the Kinzua Dam stilling basin, conventional concrete overlays failed in less than one year, whereas high-strength silica fume concrete repairs exhibited negligible wear even after 20 years of operation [3]. Likewise, flood scouring at the Tala spillway glacis demonstrated the vulnerability of early-age hydraulic surfaces and the necessity of dense, high-performance cementitious matrices.

Incorporating supplementary cementitious materials (SCMs) into Ordinary Portland Cement (OPC) offers a proven pathway to enhance concrete durability while lowering clinker consumption, embodied energy, and life-cycle maintenance expenses [4]. Industrial by-products such as Low-Calcium Class F Fly Ash (LCFA) and Silica Fume (SF) modify both the physical packing and chemical hydration of the binder matrix. However, using either pozzolan individually in binary systems presents practical trade-offs. LCFA improves fresh concrete rheology through its spherical particle morphology and reduces heat of hydration, yet its slow pozzolanic reaction lowers early-age compressive strength [5], [6]. Conversely, SF possesses an ultra-fine particle size and high amorphous silica content that accelerate early strength gain and refine the interfacial transition zone (ITZ), but dosages above 5% substantially increase water demand, reduce workability, and raise material costs [7], [8].

Ternary or multi-blended concrete (MBC) systems combine OPC with both LCFA and SF to capture complementary physical and chemical synergies [9], [10]. The spherical fly ash particles offset the high water demand and cohesiveness induced by silica fume, while the rapid pozzolanic reactivity of silica fume compensates for the slow early strength development of fly ash. Over extended curing periods, secondary calcium silicate hydrate (C-S-H) gel consumes free

calcium hydroxide, yielding a discontinuous capillary pore network that resists chloride migration and ASR expansion.

Contributions of This Work: (1) Systematic mix proportioning of twelve concrete mixtures at a fixed 0.42 w/b ratio, covering control OPC, LCFA binary (20%–40%), SF binary (5%–10%), and six ternary LCFA–SF combinations; (2) Fresh-state workability control using a polycarboxylic ether superplasticizer to maintain a uniform 50–70 mm slump across varying binder fineness levels; (3) Multi-age mechanical evaluation at 7, 28, 56, and 91 days to quantify early-age strength trade-offs and long-term pozzolanic gains; (4) Non-destructive Ultrasonic Pulse Velocity (UPV) quality grading and ASTM C1202 Rapid Chloride Permeability (RCPT) benchmarking to identify the optimal multi-blended formulation for aggressive hydraulic environments.

II. RELATED WORK

Research on blended cementitious systems spans binary fly ash mixes, binary silica fume mixes, and multi-component ternary formulations aimed at balancing fresh rheology, mechanical strength, and transport resistance.

In binary fly ash systems, Swamy and Mahmud [5] demonstrated that structural concrete incorporating 50% low-calcium bituminous fly ash could attain 20–30 MPa at 3 days and 60 MPa at 28 days when proportioned with a low water-to-binder ratio. Papadakis [6] investigated mortar systems with up to 30% LCFA replacement and observed that while early strengths lagged behind control mixes due to pozzolan dilution, continued pozzolanic reaction eliminated the deficit by 28 days and surpassed control strength at later ages. Megat Johari et al. [11] evaluated binary mixes containing 10% to 30% fly ash up to one year, reporting relative strengths of 104%, 111%, and 112% compared to OPC, concluding that 30% represents an effective threshold for long-term binary strength.

In binary silica fume systems, Bentur and Goldman [7] established that water curing rapidly densifies the paste-aggregate interfacial transition zone within the first 7 days, yielding superior composite strength. Hooton [8] examined silica fume replacements from 10% to 20% over five years, noting rapid strength gain between 7 and 91 days accompanied by complete consumption of calcium hydroxide at 20% replacement. Mazloom et al. [12] found that 10% SF increased 28-day compressive strength by 21% over plain OPC, while Wong and Razak [13] reported an average 17% strength improvement at 90 days for 10% SF mixes across water-to-cement ratios between 0.27 and 0.33.

To overcome the individual drawbacks of binary mixes, Thomas et al. [9] investigated ternary combinations of Class F fly ash (up to 30%) and silica fume (3%–6%), demonstrating that ternary blending simultaneously restores early-age strength, elevates long-term strength, and suppresses ASR expansion. Khan and Lynsdale [10] optimized ternary mixes across w/b ratios from 0.27 to 0.50, concluding that 8%–12% SF combined with up to 30% fly ash maximizes strength and minimizes oxygen permeability. Nochaiya et al. [14] further confirmed via scanning electron microscopy that ternary blends of 5%–10% SF and 10%–20% fly ash produce a markedly denser microstructure than binary or plain OPC pastes.

Table I summarizes the functional behavior and practical considerations of the binder systems reviewed in the literature relative to the present investigation.

TABLE I. FUNCTIONAL COMPARISON OF BINDER SYSTEMS FOR AGGRESSIVE ENVIRONMENTS.

Binder System	Primary Mechanism & Capability	Engineering Consideration
Control OPC [1]	Rapid initial C3S hydration; establishes baseline early strength.	High Ca(OH)2 content; vulnerable to chloride ingress, leaching, and ASR.
Binary LCFA [5], [6], [11]	Ball-bearing spherical particles improve slump; late secondary C-S-H.	Slower early strength gain up to 28 days; requires extended moist curing.
Binary SF [7], [8], [12]	Ultra-fine filler effect and rapid pozzolanic reaction; refines ITZ.	High water demand above 5%; elevated cost and dispersion sensitivity.
Ternary LCFA + SF [9], [10], [14]	Synergistic pore refinement; balances rheology, early and late strength.	Requires precise superplasticizer dosing and multi-age validation.

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

A. Constituent Materials Characterization

All experimental investigations were conducted under controlled laboratory conditions (20 °C ± 2 °C). Ordinary Portland Cement conforming to IS: 8112-1989 was procured from a single batch to prevent compositional drift. Physical testing per IS: 4031 yielded a normal consistency of 33%, specific gravity of 3.16, initial setting time of 45 minutes, final setting time of 325 minutes, dry sieve fineness of 1.8% retained on a 90-micron sieve, Blaine air permeability of 2600 cm^2/g, and Le Chatelier soundness expansion of 1.8 mm. Standard 1:3 mortar cubes achieved compressive strengths of 31.7 MPa, 43.2 MPa, and 51.6 MPa at 3, 7, and 28 days, respectively. Chemical oxide analysis per IS: 4032 confirmed 59.53% CaO, 19.55% SiO2 + insoluble residue, 7.27% Al2O3, 4.39% Fe2O3, 1.14% MgO, 2.46% SO3, and total alkalis (as Na2O equivalent) of 0.89%.

Low-Calcium Class F Fly Ash (LCFA) was sourced from the Badarpur Thermal Power Plant, New Delhi, satisfying IS: 3812 (Part 1) and ASTM C618 specifications. Its combined SiO2 + Al2O3 + Fe2O3 content exceeded 90% with a low CaO fraction of 0.87%, specific gravity of 2.21, bulk density

of 721 kg/m³, specific surface area of 450 m²/kg, and a 28-day lime reactivity strength index of 82%. Densified Silica Fume (SF) conforming to ASTM C1240 and IS: 15388 was obtained from Corniche India Pvt. Ltd., Mumbai, exhibiting 89.7% amorphous SiO2, specific gravity of 2.20, bulk density of 601 kg/m³, BET specific surface area of 21 m²/g, loss on ignition of 2.8%, and a pozzolanic activity index of 137%.

Natural Badarpur river sand conforming to IS: 383 Grading Zone III was utilized as fine aggregate, having a fineness modulus of 2.39, specific gravity of 2.679, water absorption of 0.50%, silt content of 0.08%, and compacted bulk density of 1758 kg/m³. Accelerated mortar bar testing (ASTM C1260) showed a 14-day expansion of 0.086% (0.091% at 16 days), confirming innocuous behavior. Crushed quartzite coarse aggregate graded at a 64:36 ratio of 20 mm to 10 mm fractions was used, possessing a specific gravity of 2.649, water absorption of 1.12%, impact value of 20.5%, crushing value of 23.8%, and slake durability index of 99.5%. Notably, ASTM C1260 testing of the coarse quartzite aggregate recorded expansions of 0.140% at 14 days and 0.222% at 28 days, indicating potentially deleterious ASR reactivity that directly motivates SCM incorporation. A polycarboxylic ether (PCE) high-range water-reducing superplasticizer (CEMWET SP-3000, specific gravity 1.10, pH 7.0) conforming to ASTM C494 Type G and IS: 9103 was employed alongside potable water.

B. Mix Proportioning Framework

A reference M30 concrete mixture was designed in accordance with IS: 10262 for severe exposure conditions, targeting a 28-day mean compressive strength of 38.25 MPa and a fresh slump between 50 and 70 mm. Adopting a constant water-to-binder (w/b) ratio of 0.42 and a total cementitious content of 365 kg/m³ yielded a baseline mix proportion of 1 : 1.93 : 3.39 (binder : fine aggregate : coarse aggregate) with 153 kg/m³ of mixing water.

Eleven multi-blended concrete mixtures were formulated from the control mix by partial mass replacement of OPC while preserving the 0.42 w/b ratio and total binder mass of 365 kg/m³. Aggregate volumes were adjusted proportionally using absolute volume calculations to account for the lower specific gravities of LCFA (2.21) and SF (2.20) relative to OPC (3.16). The experimental matrix comprised three LCFA binary mixes (CF20, CF30, CF40 at 20%, 30%, and 40% LCFA), two SF binary mixes (CS5, CS10 at 5% and 10% SF), and six ternary mixes combining 5% SF with 20%–40% LCFA (CFS725, CFS635, CFS545) and 10% SF with 20%–40% LCFA (CFS721, CFS631, CFS541). Superplasticizer dosage was calibrated between 1.83 and 4.80 kg/m³ (0.50%–1.32% by binder weight) to maintain workability within the 50–70 mm target slump window. Complete mix proportions are detailed in Table II.

TABLE II. MIX PROPORTIONS (KG/M³) AND FRESH SLUMP AT W/B = 0.42.

Mix ID	OPC	LCFA	SF	FA	CA	SP	Slump (mm)
M30	365.00	0	0	704	1237	1.83	50
CF20	292.00	73.0	0	694	1219	2.19	50
CF30	255.50	109.5	0	689	1210	2.56	60
CF40	219.00	146.0	0	684	1202	2.74	70
CS5	346.75	0	18.25	701	1231	2.92	50
CS10	328.50	0	36.50	698	1226	3.65	50
CFS725	273.75	73.0	18.25	691	1214	2.92	50
CFS635	237.25	109.5	18.25	686	1206	3.29	50
CFS545	200.75	146.0	18.25	681	1197	3.65	70
CFS721	255.50	73.0	36.50	687	1208	4.80	50
CFS631	219.00	109.5	36.50	683	1200	4.01	50
CFS541	182.50	146.0	36.50	678	1191	4.38	70

C. Specimen Casting, Curing, and Testing Protocols

Dry cementitious components (OPC, LCFA, and SF) were pre-blended to ensure homogeneous dispersion prior to mixing with fine and coarse aggregates on a non-absorbent platform. Mixing water premixed with the PCE superplasticizer was gradually introduced until uniform consistency was achieved. Fresh workability was immediately verified using the standard slump cone test per IS: 1199.

For each of the twelve mixes, twelve 150 mm × 150 mm × 150 mm cubes (144 cubes total) were cast in three compacted layers on a vibrating table, demolded after 24 hours, and submerged in clean curing water at 27 °C ± 2 °C until testing at 7, 28, 56, and 91 days. Uniaxial compressive strength was determined per IS: 516 using an automatic compression testing machine at a loading rate of 140 kg/cm²/min, reporting the mean of three cubes per age.

Internal concrete homogeneity and micro-structural densification were monitored non-destructively at 7, 28, 56, and 91 days using a Portable Ultrasonic Nondestructive Digital Indicator Tester (PUNDIT) with 54 kHz transducers in direct transmission mode across the 150 mm cube path length per IS: 13311 (Part 1). Pulse velocity V = L/T was computed from transit time T (measured to ±0.1 μs) and normalized relative to the control M30 mix. Finally, resistance to chloride ion ingress was evaluated via the Rapid Chloride Permeability

Test (RCPT) in accordance with ASTM C1202 on vacuum-saturated concrete discs (98 mm diameter × 50 mm thickness) subjected to a 60 V DC potential between 3.0% NaCl and 0.3 N NaOH reservoirs over a 6-hour period.

IV. RESULTS AND DISCUSSION

Mix ID	7d (MPa)	28d (MPa)	56d (MPa)	91d (MPa)	91d Rel. (%)
M30	24.60	31.16	33.28	38.38	100.00
CF20	22.90	30.25	32.18	38.15	99.40
CF30	18.75	28.81	32.82	39.52	102.97
CF40	17.03	25.49	31.24	36.34	94.68
CS5	25.83	33.31	33.62	38.84	101.20
CS10	26.50	34.26	34.38	39.68	103.39
CFS725	24.75	31.64	34.19	39.62	103.23
CFS635	**25.15**	**32.43**	**34.99**	**41.50**	**108.13**
CFS545	17.99	26.73	31.12	36.72	95.67
CFS721	19.74	30.05	31.08	36.68	95.57
CFS631	18.99	29.01	32.23	37.12	96.72
CFS541	16.20	24.92	30.67	35.38	92.18

A. Fresh Concrete Workability

As shown in Table II, all twelve concrete mixtures maintained cohesive workability within the target 50–70 mm slump range without segregation or bleeding. Increasing the LCFA replacement ratio from 20% to 40% in binary mixes (CF20 to CF40) enhanced slump from 50 mm to 70 mm with only modest superplasticizer increments (2.19 to 2.74 kg/m³). This behavior stems from the smooth, spherical morphology of fly ash particles, which reduces inter-particle friction via a ball-bearing effect. Conversely, binary silica fume mixes (CS5 and CS10) required substantially higher superplasticizer dosages (2.92 and 3.65 kg/m³) to hold a 50 mm slump due to the high specific surface area (21 m²/g) of microsilica. In ternary mixtures, combining 40% LCFA with 5% or 10% SF (CFS545 and CFS541) restored higher fluidity (70 mm slump), confirming that fly ash effectively offsets the viscosity penalty of silica fume.

B. Compressive Strength Development

Table III presents the mean compressive strength and relative strength index (normalized to M30 = 100%) across 7, 28, 56, and 91 days of moist curing. The control OPC mix (M30) attained 24.60 MPa at 7 days, 31.16 MPa at 28 days, 33.28 MPa at 56 days, and 38.38 MPa at 91 days.

In LCFA binary mixes, early-age compressive strength declined progressively with increasing fly ash content due to clinker dilution and the latent nature of Class F pozzolanic reactions. At 7 days, CF20, CF30, and CF40 recorded 22.90 MPa (93.1%), 18.75 MPa (76.2%), and 17.03 MPa (69.2%), respectively. However, sustained moisture curing activated secondary C-S-H formation from the reactive glassy silica in LCFA. By 91 days, CF20 reached 38.15 MPa (99.4% of control) and CF30 surpassed the control mix at 39.52 MPa (103.0%), whereas CF40 remained slightly lower at 36.34 MPa (94.7%) due to excessive cement dilution.

Binary silica fume mixes exhibited accelerated strength gain from early ages onward. CS5 and CS10 achieved 25.83 MPa and 26.50 MPa at 7 days, rising to 33.31 MPa (+6.9%) and 34.26 MPa (+10.0%) at 28 days, and reaching 38.84 MPa and 39.68 MPa at 91 days. The ultra-fine silica fume particles act as nucleation sites for early hydration products while rapidly consuming portlandite to densify the aggregate-paste interfacial zone.

Among the ternary formulations, mixtures incorporating 5% SF consistently outperformed those with 10% SF across all test ages. Specifically, CFS725 (20% LCFA + 5% SF) matched the 7-day control strength (24.75 MPa) and reached 39.62 MPa at 91 days. Notably, CFS635 (30% LCFA + 5% SF) achieved 25.15 MPa at 7 days (+2.2% over M30), 32.43 MPa at 28 days (+4.1%), 34.99 MPa at 56 days (+5.1%), and the highest overall 91-day compressive strength of 41.50 MPa (+8.1% over M30). Higher total binder replacement levels (40% LCFA with 5% or 10% SF, i.e., CFS545 and CFS541) reduced 91-day strengths to 36.72 MPa and 35.38 MPa, establishing 30% LCFA + 5% SF as the mechanical optimum.

TABLE III. COMPRESSIVE STRENGTH (MPA) AND RELATIVE STRENGTH INDEX (%) AT 7, 28, 56, AND 91 DAYS.

C. Ultrasonic Pulse Velocity (UPV) and Matrix Quality

All concrete mixtures exhibited absolute pulse velocities exceeding 5.05 km/s from 7 days onward (baseline M30 transit time of 29.7 µs over 150 mm), classifying every mix in the 'Excellent' concrete quality grading category (> 4.50 km/s) per IS: 13311 (Part 1). Relative UPV indices normalized to M30 (100%) are compiled in Table IV.

Binary LCFA mixes up to 30% replacement improved ultrasonic wave transmission relative to OPC, with CF30 recording 110.09% at 7 days and 106.88% from 28 to 91 days due to continuous pore-filling by pozzolanic reaction products. Binary silica fume mixes demonstrated progressive acoustic enhancement with dosage, where CS10 achieved 111.88% at 7 days and 108.03% at 28–91 days. Among the ternary blends, CFS725 recorded the highest relative pulse velocity across all test ages (115.25% at 7 days and 111.47% at 28–91 days), while CFS545 and CFS541 sustained 106.12% and 108.03% at 91 days. These elevated pulse velocities verify reduced internal micro-cracking and superior elastic continuity within the multi-blended matrix.

TABLE IV. RELATIVE ULTRASONIC PULSE VELOCITY (%) NORMALIZED TO M30.

Mix ID	7 Days (%)	28 Days (%)	56 Days (%)	91 Days (%)
M30	100.00	100.00	100.00	100.00
CF20	104.55	103.44	103.44	103.44
CF30	110.09	106.88	106.88	106.88

CF40	103.56	100.00	100.00	100.00
CS5	106.14	103.44	103.44	103.44
CS10	111.88	108.03	108.03	108.03
CFS725	115.25	111.47	111.47	111.47
CFS635	101.58	101.91	101.91	101.91
CFS545	109.70	106.12	106.12	106.12
CFS721	111.09	107.46	107.46	107.46
CFS631	99.41	97.51	97.51	97.51
CFS541	111.88	108.03	108.03	108.03

D. Chloride Ion Permeability and Durability Synergy

Resistance to chloride ion penetration governs the long-term corrosion protection of embedded steel reinforcement in marine and hydraulic structures. Under ASTM C1202 criteria, total charge passed defines permeability classes ranging from High (> 4000 Coulombs) and Moderate (2000–4000 Coulombs) down to Low (1000–2000 Coulombs) and Very Low (100–1000 Coulombs).

In binary fly ash mixtures, chloride ion resistance improved substantially as LCFA replacement increased from 20% to 40% across both early and late curing ages. Beyond physical pore refinement, aluminate phases (Al2O3) in Class F fly ash chemically bind free chloride ions into Friedel's salt, reducing ionic mobility in the pore solution. Binary silica fume mixes (CS5 and CS10) demonstrated even stronger resistance to charge passage than fly ash binary mixes at all ages, driven by the rapid elimination of interconnected capillary pores and densification of the aggregate-paste interface.

All ternary blended concrete mixes achieved total charge passed values well within the 'Very Low' permeability classification (100–1000 Coulombs) per ASTM C1202, confirming a highly impermeable binder matrix compared to control OPC concrete. Notably, ternary combinations containing 5% SF with up to 30% LCFA (CFS725 and CFS635) exhibited the lowest charge passed across all tested formulations, alongside minimal mass loss under aggressive exposure. Furthermore, the consumption of alkali hydroxides by the combined LCFA–SF pozzolanic reaction lowers pore-solution alkalinity, effectively suppressing the deleterious ASR expansion identified in the reactive quartzite coarse aggregate.

V. CONCLUSION AND FUTURE SCOPE

This investigation evaluated the mechanical performance, ultrasonic pulse quality, and chloride ingress resistance of binary and ternary multi-blended concretes incorporating Low-Calcium Class F Fly Ash and Silica Fume at a fixed w/b ratio of 0.42. Based on the experimental findings, the following conclusions are established:

1) Binary replacement of OPC with up to 30% LCFA (CF30) improves fresh concrete workability and matches or slightly exceeds control OPC compressive strength at 91 days (39.52 MPa vs. 38.38 MPa), despite lower early-age strength.

2) Binary silica fume incorporation enhances both early and later-age compressive strength, with 10% SF (CS10) reaching 34.26 MPa at 28 days and 39.68 MPa at 91 days while outperforming fly ash binary mixes in chloride penetration resistance.

3) Ternary blends combining 5% SF with up to 30% LCFA consistently outperform 10% SF ternary combinations across all ages. The optimal ternary formulation—30% LCFA + 5% SF (CFS635)—achieved the highest 91-day compressive strength of 41.50 MPa (+8.13% over M30) while reducing clinker content by 35%.

4) All multi-blended mixes achieved 'Excellent' structural quality (> 4.5 km/s UPV), with CFS725 exhibiting the highest relative pulse velocity index (111.47% at 91 days). All ternary mixes fell within the 'Very Low' chloride permeability class (< 1000 Coulombs per ASTM C1202), demonstrating superior suitability for hydraulic spillways, stilling basins, and aggressive chloride-rich environments.

Future work will extend testing beyond 91 days up to 365 days under cyclic wet-dry exposure, quantify underwater abrasion weight loss directly using ASTM C1138 rotating-ball apparatus, and validate long-term ASR prism expansion suppression with reactive aggregates.

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