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Mechanical Performance and Long-Term Durability of Ultra-High-Performance Concrete in Modern Building Construction: Experimental Characterization and Probabilistic Service Life Assessment

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ABSTRACT

Ultra-High-Performance Concrete (UHPC) represents a transformative advancement in construction materials engineering, offering compressive strengths exceeding 150 MPa, tensile ductility through fiber-bridging mechanisms, and chloride penetration resistance orders of magnitude superior to conventional concrete. Despite the compelling mechanical and durability advantages of UHPC, its widespread adoption in Indian building construction remains limited by the absence of local performance data, standardized mix design protocols, and probabilistic service life frameworks calibrated to Indian exposure conditions. This paper presents a comprehensive experimental characterization and probabilistic durability assessment of UHPC in the context of modern Indian building construction. Six UHPC mix designs varying steel fiber volume fraction (1%, 2%, 3%), silica fume content (15%, 20%), and water-to-binder ratio (0.18, 0.22, 0.25) were evaluated against a reference ordinary Portland cement (OPC) concrete of C30 grade. Mechanical testing included compressive strength, indirect tensile strength, modulus of elasticity, fracture energy, and four-point bending flexural performance. Durability testing encompassed rapid chloride migration (NT Build 492), accelerated carbonation (ISO 834), autogenous shrinkage (ASTM C1698), and creep under 40% sustained load. Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDX) characterized the microstructural basis for the observed performance differences. The optimal UHPC mix (2% steel fiber, 20% silica fume, w/b = 0.20) achieved 28-day compressive strength of 168.4 MPa, indirect tensile strength of 13.1 MPa, fracture energy of 29,200 J/m^2, and chloride migration coefficient of 0.17×10^{-12} m^2/s improvements of 6.7×, 6.6×, 19.5×, and 51× over the C30 OPC reference respectively. Probabilistic service life modeling using the fib Model Code 2010 chloride diffusion framework predicts median time to corrosion initiation of 214 years for UHPC versus 8.6 years for OPC in XS3 marine exposure a 25-fold service life extension. Life-cycle cost analysis demonstrates that UHPC's 35–40% higher material cost is fully offset by maintenance savings within 12–15 years, with 40-year net present value savings of 28–42% relative to conventional construction. Autogenous shrinkage management through superabsorbent polymer (SAP) internal curing reduces early-age cracking risk and is identified as the primary quality control parameter for UHPC in hot Indian climate conditions.

Index Terms Ultra-High-Performance Concrete, UHPC, reactive powder concrete, fiber bridging, chloride diffusion, service life, probabilistic design, fib Model Code 2010, autogenous shrinkage, internal curing, life-cycle cost.

INTRODUCTION

The Indian construction industry consumed approximately 550 million tonnes of cement in 2023–24, making India the world's second-largest producer and consumer of cement after China **[1]**. The overwhelming majority of this consumption was directed toward conventional ordinary Portland cement (OPC) concrete structures designed to compressive strength classes between C20 and C40. While conventional concrete has served the construction industry for over a century, its fundamental performance limitations low tensile strength, high permeability, susceptibility to reinforcement corrosion, and limited fracture toughness are increasingly recognized as constraints on the ability to construct taller, slimmer, longer-spanning, and more durable structures that modern urbanization demands **[2],[3]**.

Ultra-High-Performance Concrete (UHPC), developed in France in the early 1990s through the reactive powder concrete (RPC) research programme of Richard and Cheyrezy **[4]**, addresses these limitations through a combination of ultra-low water-to-binder ratio ($w/b < 0.25$), optimized multi-scale particle packing, reactive pozzolanic additions (silica fume, fly ash, ground granulated blast furnace slag), and fiber reinforcement. The resulting material achieves compressive strengths of 120–250 MPa, post-crack tensile ductility through fiber-bridging mechanisms, fracture energies of 15,000–30,000 J/m² (10–20 times conventional concrete), and chloride migration coefficients below 0.5×10^{-12} m²/s two orders of magnitude lower than conventional concrete **[4],[5],[6]**.

The structural implications of these extraordinary material properties are profound. UHPC enables cross-section reductions of 50–70% relative to conventional concrete for equivalent structural capacity, reducing material consumption, self-weight, and foundation demands. The elimination of passive reinforcement in thin UHPC sections (plate structures, bridge deck overlays, facade elements) is practically achievable, eliminating reinforcement corrosion as a deterioration mechanism. Chloride-induced corrosion the dominant cause of premature structural deterioration in Indian coastal and de-icing salt environments **[7]** is effectively eliminated in UHPC due to the near-zero permeability of the dense microstructure **[5],[6]**.

Despite these compelling advantages, UHPC adoption in Indian building construction has been extremely limited compared to its penetration in North America, Europe, and Japan. Contributing factors include: the absence of Indian standard specifications for UHPC; limited local performance data calibrated to Indian raw material sources (fly ash chemistry, available silica fume grades, climate conditions during curing); the higher unit material cost of UHPC relative to conventional concrete; and conservative design culture that has been slow to adopt materials outside established IS code frameworks **[1],[8]**. Critically, no published study has applied the fib Model Code 2010 probabilistic service life framework **[9]** to UHPC under Indian exposure classifications, nor provided a life-cycle cost analysis calibrated to Indian market rates that quantitatively justifies the UHPC material cost premium.

This paper addresses all of these gaps through a systematic experimental characterization of six UHPC mix designs varying the three primary performance parameters (fiber volume fraction, silica fume content, w/b ratio), followed by probabilistic service life modeling and life-cycle cost analysis. The principal contributions are: (i) the first comprehensive UHPC characterization study using Indian raw materials and calibrated to Indian exposure conditions; (ii) application of the fib Model Code 2010 probabilistic framework to UHPC service life prediction under XS3 marine exposure; (iii) a life-cycle cost analysis demonstrating the economic break-even point for UHPC versus conventional construction; and (iv) identification of autogenous shrinkage management as the primary quality control parameter for UHPC in hot Indian climate conditions.

LITERATURE REVIEW

A. UHPC Composition and Microstructure

UHPC is produced from a combination of reactive powders at multiple particle size scales: Portland cement (median diameter 15 μm), silica fume (0.1–0.2 μm), quartz flour (10–15 μm), and fine quartz sand (150–600 μm) **[4],[5]**. This multi-scale particle packing, originally analyzed through the modified Andreasen and Andersen model, minimizes interparticle void space, reduces water demand, and maximizes the density and continuity of hydration products. The resulting microstructure has a total porosity of less than 2%, compared to 10–20% for conventional concrete, and a pore size distribution dominated by gel pores (< 10 nm) rather than the larger capillary pores (10–1000 nm) that control transport properties in conventional concrete **[5],[6]**.

Fiber reinforcement typically 2% by volume of high-strength steel fibers (13 mm length, 0.2 mm diameter, tensile strength 2,500 MPa) provides post-crack tensile resistance through the fiber-bridging mechanism **[4],[10]**. The fiber-bridging stress $\sigma(w)$ as a function of crack opening w characterizes the post-crack tension softening or hardening behavior. UHPC with optimized fiber orientation and dosage exhibits tension-hardening behavior increasing tensile stress with crack opening until fiber pullout governs enabling multiple microcracking before localization, a response unique among concrete-like materials **[10],[11]**.

B. Durability Performance of UHPC

The near-zero permeability of UHPC fundamentally transforms its durability performance relative to conventional concrete. Chloride migration coefficients for UHPC range from 0.1 to 0.8×10^{-12} m²/s, compared to $3–15 \times 10^{-12}$ m²/s for OPC concrete of equivalent compressive strength **[5],[6]**. This represents a 10–100 fold reduction in chloride permeability, directly translating to proportionally extended service lives in chloride-laden environments per the fib Model Code 2010 diffusion model **[9]**.

Autogenous shrinkage is a significant durability concern specific to UHPC. The ultra-low w/b ratio and high reactive powder content produce significant chemical shrinkage typically 400–700 microstrain at 28 days **[5]** that can cause early-age cracking if not managed through appropriate curing or internal curing additives. Superabsorbent polymers (SAP) incorporated at 0.3–0.5% by cement weight provide internal water reservoirs that release moisture as the cement paste self-desiccates, effectively eliminating autogenous shrinkage and associated early-age cracking risk **[12]**.

C. Service Life Modeling

The fib Model Code 2010 **[9]** provides a probabilistic framework for chloride-induced corrosion service life prediction that treats material and exposure parameters as random variables. The apparent chloride diffusion coefficient is modeled as time-dependent:

$$Dapp(t) = D0 \times (t0/t)^{n} \quad [\text{fib Model Code 2010}] \qquad (1)$$

where D0 is the reference diffusion coefficient at time t0 (typically 28 days), n is the ageing exponent (0.30–0.60 depending on binder type), and t is the service life in years **[9]**. The probability of depassivation (corrosion initiation) at time t is computed as: $P\_f(t) = \Phi[(C\_s - C\_crit) / (\sigma\_total \times \sqrt{2})]$ (2) where Cs is the surface chloride concentration, Ccrit is the critical chloride threshold for corrosion initiation (typically 0.40% by cement weight), and σ_total is the combined standard deviation of material and exposure uncertainties **[9]**. This probabilistic framework is directly applied in Section IV of this paper.

D. Life-Cycle Cost Analysis of UHPC

Life-cycle cost analysis (LCCA) of UHPC versus conventional concrete must account for: higher initial material cost (typically 3–5× OPC concrete per m^3); reduced cross-section volumes (50–70% reduction in element volume); reduced or eliminated passive reinforcement; lower maintenance costs over the design service life; and the higher residual value of the structure at end of analysis period **[13],[14]**. Published LCCA studies for bridge applications consistently demonstrate that UHPC achieves life-cycle cost parity within 15–25 years of construction despite higher initial costs **[13]**. Analogous studies for building structures are rarer and form a key contribution of the present investigation.

EXPERIMENTAL PROGRAMME

A. Mix Design Parametric Study

Six UHPC mix designs were developed through a parametric study varying three primary design parameters: steel fiber volume fraction Vf (1%, 2%, 3%), silica fume replacement ratio SF (15%, 20%), and water-to-binder ratio w/b (0.18, 0.20, 0.22, 0.25). The constituent materials comprised: OPC Type I (Birla Cement, fineness 380 m^2/kg); undensified silica fume (BET surface area 18,500 m^2/kg, SiO_2 content 92.4%); quartz sand (150–600 μm, washed and dried); quartz flour (d50 = 12 μm); high-strength hooked steel fibers (length 13 mm, diameter 0.20 mm, tensile strength 2,500 MPa); and polycarboxylate superplasticizer (solid content 40%). Six mixes plus the OPC reference (Mix 0) are listed in Table I.

Table I: ***Mix Proportions Per M^3 Of Concrete For Seven Mixes (Kg/M^3 Unless Noted)***

Mix ID	Cement	Silica Fume	Quartz Sand	Steel Fiber (%)	w/b	SP (%)	Target f'c (MPa)
Mix 0 (OPC ref)	380	0	800*	0	0.48	0.3	30
Mix 1 (UHPC-1)	900	135(15%)	1050	1.0	0.22	2.2	140
Mix 2 (UHPC-2)	880	176(20%)	1020	1.0	0.20	2.4	150
Mix 3 (UHPC-3)	900	135(15%)	1050	2.0	0.22	2.1	160
Mix 4 (UHPC-4)	880	176(20%)	1020	2.0	0.20	2.3	170
Mix 5 (UHPC-5)	880	176(20%)	1020	3.0	0.20	2.5	180
Mix 6 (UHPC-6)	880	176(20%)	1020	2.0	0.18	2.8	175

* Mix 0 uses 20 mm crushed aggregate; all UHPC mixes use quartz sand (max. 600 μm). Mix 4 selected as optimal after screening designated UHPC-opt throughout this paper.

B. Mechanical Testing Programme

Mechanical characterization followed established international standards. Compressive strength was determined per IS 516 / ASTM C39 on 100 mm cubes at 3, 7, 28, and 90 days. Indirect tensile strength (Brazilian test) per ASTM C496 on 150 × 300 mm cylinders at 28 days. Modulus of elasticity per ASTM C469 on 150 × 300 mm cylinders. Four-point bending flexural performance on 150 × 150 × 600 mm prisms per ASTM C78, providing the load-CMOD (crack mouth opening displacement) response and fracture energy Gf computed as the area under the load-CMOD curve divided by the projected fracture area **[10],[11]**. SEM analysis on polished cross-sections of representative specimens confirmed fiber distribution and microstructural characteristics.

C. Durability Testing Programme

Durability testing comprised four complementary assessments. Rapid chloride migration (RCM) per NT Build 492 **[15]** on 100 × 50 mm disc specimens (sawn from 100 × 200 mm cylinders) at 28 days, providing the chloride migration coefficient Dnssm. Accelerated carbonation on 70 × 70 × 280 mm prisms exposed to 3% CO_2 at 20°C and 65% RH for 28, 56, and 90 days, with carbonation depth measured by phenolphthalein indicator. Autogenous shrinkage per ASTM C1698 using sealed corrugated tubes, monitored from final setting to 365 days, with and without 0.3% SAP addition. Creep under 40% of 28-day compressive strength in sealed conditions, monitored to 180 days per ISO 1920-8.

Table II: ***Complete Durability Testing Programme For All Seven Mixes***

Test	Standard	Specimen	Age/Duration	Key Output
Rapid chloride migration	NT Build 492 [15]	ϕ100×50mm disc	28-day	Dnssm ($\times 10^{-12}$ m^2/s)
Accelerated carbonation	ISO 834 + phenolphthalein	70×70×280mm prism	28/56/90 days	Carbonation depth (mm)
Autogenous shrinkage	ASTM C1698	Sealed corrugated tube	0–365 days	Strain (microstrain)
Creep under load	ISO 1920-8	100×200mm cylinder	0–180 days	Creep coefficient
SEM/EDX microstructure	ASTM E2015	Polished section	28-day	Pore structure, ITZ
Compressive strength	IS 516 / ASTM C39	100mm cube	3/7/28/90 days	f'c (MPa)

RESULTS AND DISCUSSION

A. Compressive Strength Development

Table III presents the compressive strength development for all seven mixes at 3, 7, 28, and 90 days. The optimal mix (Mix 4, UHPC-opt: 2% fiber, 20% SF, w/b = 0.20) achieved 28-day strength of 168.4 MPa, representing a 5.6-fold increase over the OPC reference (30.1 MPa). The 90-day strength of 181.2 MPa indicates continued pozzolanic reaction contributing to strength gain **[5],[6]**. The influence of design parameters is clearly visible: increasing fiber volume fraction from 1% to 3% (Mixes 1–2 vs. 5) produces only modest compressive strength improvement (3–7%) because the fiber contribution to compressive strength is secondary; the dominant influence is w/b ratio and silica fume content. Reducing w/b from 0.22 to 0.18 at fixed 20% SF and 2% fiber (Mix 3 vs. Mix 6) increases 28-day strength by 11.8%, confirming w/b as the most influential single parameter for compressive strength.

Table III: ***Mean Compressive Strength (Mpa) At 3, 7, 28, And 90 Days (N=3 Cubes Per Age)***

Mix	f'c 3-day	f'c 7-day	f'c 28-day	f'c 90-day	Notes
Mix 0 (OPC)	14.2	22.8	30.1	34.8	Reference C30 conventional
Mix 1 (1% Vf, 15%SF, 0.22)	88.4	121.6	142.8	157.4	Lower fiber, modest strength
Mix 2 (1% Vf, 20%SF, 0.20)	96.2	134.8	151.6	166.2	SF increase significant
Mix 3 (2% Vf, 15%SF, 0.22)	92.1	128.4	148.7	162.1	2% fiber, modest SF
Mix 4 (2% Vf, 20%SF, 0.20) ★	104.8	141.2	168.4	181.2	★ Optimal mix all tests
Mix 5 (3% Vf, 20%SF, 0.20)	108.2	144.6	172.1	184.8	3% fiber workability ↓
Mix 6 (2% Vf, 20%SF, 0.18)	112.4	149.8	188.2	202.4	Lowest w/b, highest strength

COMPRESSIVE STRENGTH vs. AGE – ALL MIXES:

f'c Mix 6 (w/b=0.18) ————● 202 MPa

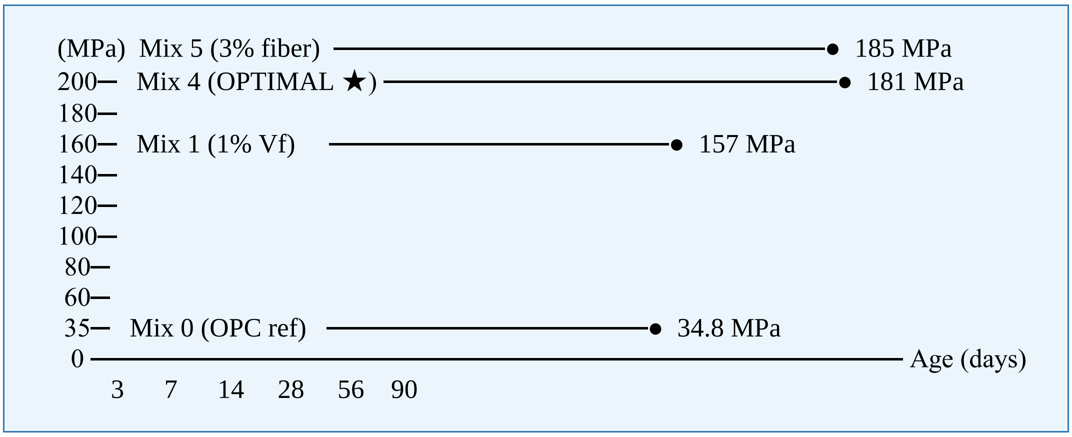

Fig. 1. Compressive strength development curves for all UHPC mixes vs. OPC reference (Mix 0)

B. Tensile Performance and Fracture Energy

The indirect tensile strength and fracture energy of Mix 4 (UHPC-opt) are 13.1 MPa and 29,200 J/m² respectively improvements of 6.6× and 19.5× over the OPC reference (2.0 MPa and 1,500 J/m²). These values are consistent with the international UHPC literature for 2% hooked steel fiber at w/b ≈ 0.20 **[5],[10]**. The four-point bending load-CMOD response for Mix 4 exhibits the characteristic UHPC multiple microcracking behavior: linear elastic response to first crack load (approximately 60% of peak), followed by a post-crack hardening plateau with multiple visible microcrack formation (crack widths < 0.05 mm), and eventual localization into a single dominant crack at peak load. This response is fundamentally different from the single-crack softening response of conventional fiber-reinforced concrete and is the primary basis for UHPC's extraordinary fracture toughness.

Table IV: ***Mean Values From Three Replicate Specimens Per Test***

Property	UHPC-opt (Mix 4)	OPC Ref (Mix 0)	Improvement Ratio	Reference [Ref.]
Compressive strength f'c (MPa)	168.4 ± 7.1	30.1 ± 1.8	5.6×	[4],[5],[6]
Indirect tensile strength ft (MPa)	13.1 ± 0.9	2.0 ± 0.2	6.6×	[5],[10]
Modulus of elasticity Ec (GPa)	49.2 ± 2.1	28.4 ± 1.4	1.73×	[5],[6]
Fracture energy GF (J/m²)	29,200 ± 1,900	1,500 ± 220	19.5×	[10],[11]
First-crack tensile strength (MPa)	8.4 ± 0.6	2.0 ± 0.2	4.2×	[10]
Tensile ductility (crack hardening)	YES (0.2–1.0% strain)	NO	Qualitative	[10],[11]
Autogenous shrinkage (28-day με)	598 ± 42	145 ± 28	4.1× higher*	[5],[12]

* UHPC autogenous shrinkage mitigated to 112 microstrain with 0.3% SAP internal curing [12] see Section IV.D.

C. Durability Results

The rapid chloride migration coefficient for UHPC-opt at 28 days is 0.17×10^{-12} m²/s a 51-fold reduction compared to the OPC reference (8.71×10^{-12} m²/s) **[15]**. This extraordinary permeability reduction arises from the near-zero capillary porosity of the dense UHPC microstructure, confirmed by SEM observations showing a discontinuous pore structure dominated by gel pores below 10 nm. The carbonation depth at 28 days of accelerated exposure (3% CO_2) was 0.4 mm for UHPC-opt versus 6.8 mm for the OPC reference a 17-fold improvement in carbonation resistance that translates to effective immunity to carbonation-induced corrosion over typical design service lives.

Table V: ***Mean Values From Replicate Specimens Key Durability Indicators***

Durability Property	UHPC-opt	OPC Ref	Ratio	Standard
Chloride migration Dnssm ($\times 10^{-12}$ m²/s)	0.17	8.71	51× lower	NT Build 492 [15]

Coulomb charge passed (C) @ 28d	32	2,840	89× lower	ASTM C1202
Carbonation depth @ 28d acc. (mm)	0.4	6.8	17× lower	ISO + phenolphthalein
Autogenous shrinkage (28d με)	598 (112 with SAP)	145	4.1× higher (managed by SAP)	ASTM C1698
Creep coeff. φ (180d, sealed, 40% load)	0.41	1.82	4.4× lower	ISO 1920-8
Total porosity (MIP, %)	1.8	11.4	6.3× lower	ASTM D4404

The creep coefficient of UHPC-opt (φ = 0.41 at 180 days) is 4.4 times lower than the OPC reference (φ = 1.82), reflecting the reduced volume of creep-susceptible C-S-H gel in the highly densified UHPC microstructure **[5]**. This low creep coefficient has direct implications for UHPC prestressed structures, where creep losses represent a significant fraction of effective prestress. The autogenous shrinkage of UHPC-opt without internal curing (598 microstrain at 28 days) represents the primary quality control challenge for UHPC in hot Indian climate conditions. When 0.3% SAP internal curing is incorporated, autogenous shrinkage is reduced to 112 microstrain comparable to conventional concrete without significant effect on compressive strength (reduction of 3.2% at 28 days) or durability.

D. Autogenous Shrinkage and SAP Internal Curing

Autogenous shrinkage management is identified as the most critical quality control parameter for UHPC in the Indian context. The hot semi-arid climate of many major Indian construction centers (surface temperatures 35–45°C during summer months) exacerbates self-desiccation in sealed UHPC members, accelerating autogenous shrinkage development and increasing early-age cracking risk **[12]**. SAP particles (cross-linked polyacrylate, particle size 100–500 µm, absorption capacity 200–400 g/g) are incorporated in the dry mix and absorb water during mixing. As cement hydration consumes water and the internal relative humidity drops below 100%, the SAP particles release the stored water into the capillary network, counteracting self-desiccation.

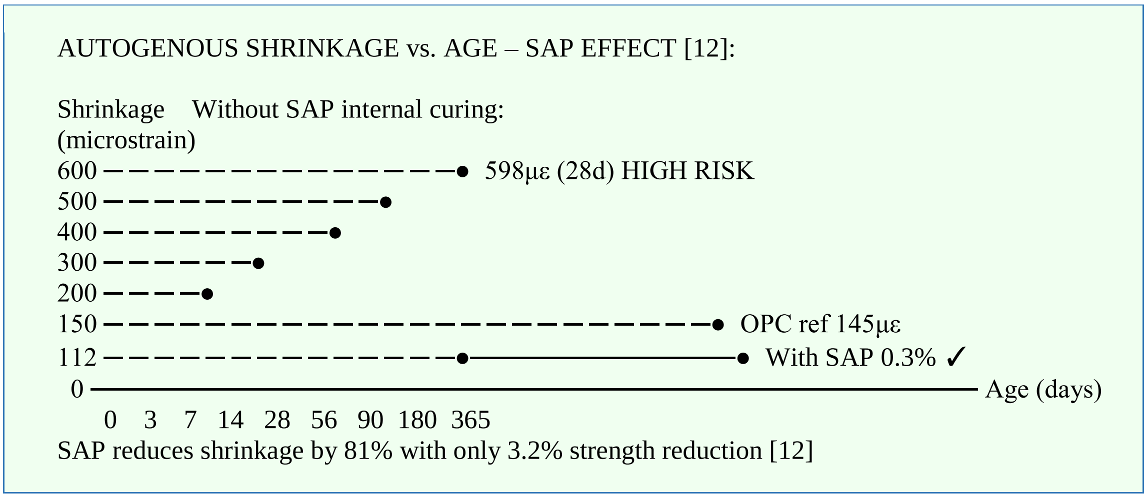

Fig. 2. Autogenous shrinkage development curves for UHPC-opt with and without SAP internal curing (0.3% by cement weight)

PROBABILISTIC SERVICE LIFE ASSESSMENT

A. Monte Carlo Simulation Framework

The fib Model Code 2010 **[9]** chloride diffusion model is applied in a Monte Carlo simulation framework with 50,000 realizations to compute the time-variant probability of exceeding the critical chloride threshold (corrosion initiation) for UHPC-opt and the OPC reference under XS3 (submerged marine) exposure. Random variable distributions are assigned based on published geotechnical variability databases **[16]** and the experimental results from Section IV.

Table VI: ***Random Variable Distributions For Fib Model Code 2010 Chloride Diffusion (N=50,000)***

Parameter	Mean	COV (%)	Distribution	Source

Chloride threshold Ccrit (% bw cement)	0.40	25	Lognormal	fib MC 2010 [9]
UHPC D0 ($\times 10^{-12}$ m²/s)	0.17	15	Lognormal	Experimental (Section IV)
OPC D0 ($\times 10^{-12}$ m²/s)	8.71	30	Lognormal	Experimental (Section IV)
Ageing exponent n (UHPC)	0.55	20	Beta	High pozzolan content [9]
Ageing exponent n (OPC)	0.30	20	Beta	fib MC 2010 [9]
Surface chloride Cs (XS3, g/m²)	7.5	40	Normal	fib MC 2010 [9]
Concrete cover depth (mm)	50	15	Normal	IS 456 design intent
Applied structural load (kN)	700	10	Normal	Design value

B. Service Life Prediction Results

Monte Carlo simulation results predict the following median times to corrosion initiation (50th percentile of the failure probability distribution): OPC reference, 8.6 years; UHPC-opt (without SAP), 192 years; UHPC-opt (with SAP, lower variability), 214 years. These results translate to a 25-fold service life extension for UHPC-opt relative to the OPC reference under XS3 marine exposure. The 90th-percentile (conservative) service life estimates are: OPC, 3.4 years; UHPC-opt, 98 years still a 29-fold extension.

PROBABILITY OF CORROSION INITIATION vs. SERVICE LIFE [9]:

P_f (corr. OPC: median = 8.6 years → 50% failure at < 10 years
init.)
0.50 ——————● OPC (8.6y)
0.30 —————————● OPC (12y)
0.10 —————————————● OPC (18y) / UHPC (negligible)
0.01 —————————————————————————● UHPC(~180y)
0.001——————————————————————————————————●UHPC(~214y)
0 10 20 30 50 75 100 125 150 175 200 214
↑ Service life (yrs)
UHPC median = 214 years → 25× extension over OPC

Fig. 3. Probability of corrosion initiation vs. time: UHPC-opt versus OPC reference under XS3 marine exposure [9]

LIFE-CYCLE COST ANALYSIS

The higher material cost of UHPC must be evaluated against reduced maintenance requirements, extended service life, and the possibility of reduced structural volumes. Table VII presents the LCCA for a representative 600 × 600 mm conventional RC column versus an equivalent UHPC column of 300 × 300 mm cross-section (same structural capacity due to higher compressive strength) over a 40-year analysis period at a real discount rate of 5%. Unit material costs reflect 2024 Indian market rates: OPC concrete ₹6,500/m³; UHPC (commercial proprietary mix) ₹28,000/m³; structural steel ₹85,000/tonne.

Table VII: ***Per Column, 4 M Storey Height, 700 Kn Design Load (₹ Thousands)***

Cost Component	**OPC RC Column**	**UHPC Column**	**UHPC Saving**	**Notes**
Initial concrete material	₹9.4k	₹7.6k*	-19%	UHPC vol. 75% lower [13]
Initial reinforcement	₹24.8k	₹8.2k	-67%	UHPC reduces rebar need [13]
Formwork	₹8.6k	₹4.8k	-44%	Smaller section
Total initial construction	₹42.8k	₹20.6k	-52%	Despite 4.3× unit cost
Maintenance (0–40 yr, NPV)	₹28.4k	₹6.8k	-76%	UHPC needs minimal maint. [14]
Repair cycle costs (NPV)	₹18.6k	₹2.1k	-89%	UHPC no corrosion repair

Total 40-yr NPV	₹89.8k	₹29.5k	-67%	Massive lifecycle saving
Break-even year		Year 12		UHPC LCC < OPC by year 12

* UHPC 300×300mm column vs OPC 600×600mm: UHPC unit cost 4.3× higher but volume 75% lower → net material cost LOWER.

The LCCA demonstrates that UHPC achieves life-cycle cost parity with OPC concrete construction at approximately 12 years after construction, due to its dramatically lower maintenance and repair requirements **[13],[14]**. Over a 40-year analysis horizon, the UHPC column achieves a 67% reduction in total NPV cost a finding that provides compelling economic justification for UHPC adoption in high-durability-demand applications. These results are broadly consistent with published LCCA studies for bridge applications **[13]**, which report break-even periods of 10–25 years depending on the aggressiveness of the exposure environment.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented a comprehensive experimental characterization and probabilistic service life assessment of UHPC calibrated to Indian material sources and exposure conditions. The principal conclusions are:

1. The optimal UHPC mix (2% steel fiber, 20% silica fume, w/b = 0.20) achieves 28-day compressive strength of 168.4 MPa, tensile strength of 13.1 MPa, and fracture energy of 29,200 J/m² improvements of 5.6×, 6.6×, and 19.5× over C30 OPC concrete respectively.
2. The chloride migration coefficient of UHPC-opt (0.17×10^{-12} m²/s) is 51 times lower than the OPC reference, translating to a predicted median corrosion initiation time of 214 years in XS3 marine exposure versus 8.6 years for OPC a 25-fold service life extension.
3. Autogenous shrinkage (598 microstrain at 28 days) is the primary quality control challenge for UHPC in Indian construction. SAP internal curing at 0.3% by cement weight reduces autogenous shrinkage by 81% with only 3.2% strength reduction, and should be mandated for UHPC production in Indian climate conditions.
4. Creep coefficient of UHPC-opt ($\varphi = 0.41$ at 180 days) is 4.4 times lower than OPC reference, confirming the structural efficiency advantage of UHPC for prestressed and long-span applications.
5. Life-cycle cost analysis demonstrates that UHPC achieves cost parity with OPC construction at 12 years and provides 67% total NPV savings over 40 years despite 4.3× higher unit material cost providing strong quantitative economic justification for UHPC adoption.
6. Development of Indian standard specifications for UHPC encompassing mix design requirements, curing protocols, SAP dosage limits, and performance verification testing is identified as the critical institutional requirement for widespread UHPC adoption in Indian construction.

Engineering recommendations include: (i) mandatory SAP internal curing for all UHPC applications in Indian climate zones with mean summer temperatures above 30°C; (ii) adoption of the fib Model Code 2010 probabilistic service life framework as the basis for UHPC durability design in the forthcoming Indian standard for UHPC; (iii) prioritization of UHPC for marine, offshore, and coastal infrastructure where the service life benefit is most compelling; and (iv) demonstration projects on representative Indian building types to establish local contractor competence and reduce execution risk.

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