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ENHANCING STRUCTURAL EFFICIENCY OF RCC MEMBERS WITH HIGH-PERFORMANCE CONCRETE

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Abstract

The use of high-performance concrete (HPC) in the structural optimization of reinforced concrete (RCC) members is a field of contemporary civil engineering with the potential of achieving simultaneously the aforementioned requirements (of high demand for load-bearing capacity, durability and material efficiency). This experimental study focuses on the structural behavioral and optimization possibilities in RCC beams, columns & slabs containing high-performance concrete (HPC) mixes with a wide range of compressive strengths between 60 MPa and 120 MPa along with some supplementary cementitious materials (SCMs) like silica fume, fly ash, & ground granulated blast-furnace slag (GGBS). Monotonic and cyclic load tests were performed on 120 RCC specimens, and the results of deflection, crack width, ductility index, and ultimate load capacity were compared with those of conventional concrete (CC) of characteristic strength between 25 and 30 MPa. We used statistical analysis with regression modeling, analysis of variance (ANOVA), and multi-objective optimization methods on the experimental dataset to obtain optimized section dimensions and reinforcement ratios. Results show that, while retaining comparable structural performance, cross-sectional area reduction of 28–47% and 35% service life improvement under extreme environmental exposure are possible using HPC-based RCC members. Overall, the implications of these findings for making sustainable construction are significant, including material saving, reduced dead loads and improved seismic performance. The results are supported by a comparison with existing studies validating the empirical proof of potential for HPC as a disruptive technology to accelerate structural design optimization.
Keywords: *High-Performance Concrete (HPC); RCC Structural Optimization; Compressive Strength; Supplementary Cementitious Materials; Ductility Index; Seismic Performance; Durability Enhancement.*

1. Introduction

Reinforced concrete (RCC) continues to be the most widely employed composite structural material in the world, supporting the full range of infrastructure from residential and bridges to high-rise towers and industrial buildings. Although ubiquitous, traditional concrete (CC) mixes, which are usually characterized by FCK of 20–30 MPa, become severely hampered in current structural applications due to demands for higher load capability, reduced structural mass, and resistance to environmental degradation. These are two pressing imperatives that the global construction industry must increasingly grapple with, often in a dualistic manner: structural performance and sustainability. High-Performance Concrete (HPC) finally defined as concrete with compressive strength above 55 MPa and with enhanced workability, durability, and mechanical properties is an attractive technical and economical solution to these problems according to ACI Committee 363. The reduction in cross-sectional dimensions of beams and columns reduces self-weight loads, enhances architectural flexibility and contributes to the overall structural efficiency of built systems and infrastructure through the design and optimization of RCC members integrated with HPC as an engineered solution. However, empirical quantification of these benefits of optimized heat dissipation across the entire life cycle is still lacking, specifically across extrapolation conditions of tropical climatic exposure in the Indian subcontinent.

1.1 Background and Motivation

The motivation behind this research stems from the intersection of three important realities in engineering. Yousef M. Fadali in your case, India as developing country has more Pressure of Urbanization calling for future taller thinner, and materially efficient structures within an increasingly limited urban footprint. Second, the realization of the greenhouse gas emissions associated with the manufacture of Portland cement estimated to be at least 0.8–1.0 tons of CO_2 emissions per ton of cement produced has motivated the development of lesser clinker content HPC formulations, by including supplementary cementitious materials (SCMs), that can simultaneously enhance structural concrete performance. Thirdly, codal provisions of IS 456:2000 and IS 10262:2019 pertaining to Indian RCC design is primarily calibrated for conventional grade of concrete (M20–M35) and there are no explicit guidelines on structural optimization of RCC members using HPC (M60–M120). HPC is helpful in theory, but is not so readily applicable in practice due to this knowledge gap, which is a practical barrier for structural engineers looking to transition HPC into commonplace projects.

1.2 Objectives of the Study

This study pursues four primary objectives to experimentally characterize the mechanical and durability properties of HPC mixes incorporating silica fume, fly ash, and GGBS at varied replacement levels; to evaluate the structural performance of RCC beams, columns, and slabs fabricated with HPC under monotonic and cyclic loading, benchmarked against conventional concrete specimens; to apply statistical optimization methodologies including multiple regression analysis, ANOVA, and multi-objective optimization to identify optimal section dimensions and steel reinforcement ratios that minimize material usage while satisfying IS 456:2000 serviceability and ultimate limit state criteria; and to quantitatively assess the durability and life-cycle performance improvements associated with HPC-based structural optimization. By addressing these objectives, the study generates an empirical dataset and optimization framework of direct utility to practicing structural engineers, researchers, and policy-makers engaged with the Indian construction sector.

1.3 Significance and Scope

Theoretical and Practical importance of the research It advances the field of research in HPC structural mechanics by offering experimental data on the load-deflection response, cracking response and then ductility characteristics of optimized RCC members. On a practical level, the optimization results allow quantification of savings in material, structural efficiency indexes, and life cycle cost reductions, which support the business case for the use of HPC in Indian construction projects. The study fulfills three types of structural elements beams, columns, and two-way slabs produced in three different concrete grades of conventional M30, and HPC grades M60 and M100. Tests were carried out under laboratory conditions at the Civil Engineering Research Laboratory of the morphological laboratory and to study its resistance against the simulated marine chloride exposure. Although no dynamic seismic loading is applied for full-scale tests, the seismic performance indices are estimated through the ductility and energy absorption data. Overall, the findings are projected to be of universal relevance for structural optimization studies in tropical and semi-arid climates.

2. Literature Survey

In the face of innovations in materials science and computational structural engineering, interest in the structural optimization of reinforced concrete (RCC) members using high-performance concrete has received considerable attention over the last thirty years. Notably, an early, seminal treatment of high-performance concrete (HPC) by Aïtcin [1] demonstrated that concrete with water-to-binder ratios (W/B) less than 0.35 and compressive strengths exceeding 60 MPa displays qualitatively different, superior structural behavior compared to normal-strength concrete, including reduced creep and lower permeability and different crack propagation. More recent work by Neville [1] discussed the microstructural mechanisms which impart enhanced performance to high-performance concrete (HPC) in which the interfacial transition zone (ITZ) between aggregate and cement paste plays a major role in the aggregate–paste in the preferential path of stress transfer between adjacent constituents to control strength also the durability by inducing micro crack in such way that protect the action of external aggressive agents washing away all the toxins [2]. Their extensive literature review (de Larrard and Sedran 1994) on the optimization of high-performance concrete (HPC) mix design using the compressible packing model formed a quantitative basis on which the proportions of constituent material are related to resulting mechanical properties [3]. The work of Sarkar et al. Finite Element Analysis by Aly et al. (2012) proved HPC columns could achieve the same axial capacity as comparable conventional concrete columns but with a 30-40% reduction in cross-sectional area, supporting the experimental findings from previous studies reported by 4 Shah and Ahmad (1994). Although the experimental study of Pham and Hao (2016) reported that normal-strength concrete beams improved substantially on energy absorption capacity the critical parameter in seismic design when compared to HPC beams, specimens with HPC experienced 1.8–2.5 times greater ductility ratios under similar reinforcement ratios [6]. In parallel studies, Bernardo and Lopes (2004) evaluated the flexural ductility of HPC beams and observed a more brittle post-peak response in HPC than normal concrete, unless confinement reinforcement was optimally detailed, thus emphasizing optimization of detailing versus mix design [7].

A large body of research has focused on the use of supplementary cementitious materials (SCMs) in HPC mixes, looking at technical performance and environmental benefits. Silica fume replaces 5–15% of the cement mass and it will react-pozzolanic reaction and micro-filler effects which lead to enhanced density of the microstructure and will increase compressive strength from 15 to 25% as well as significantly decrease in chloride permeability [8] According to Berry and Malhotra [9], Fly ash improves workability due to its spherical particle morphology, lowers heat of hydration beneficial for mass concrete, and contributes to long-term strength gain when used at 20–35% replacement. Oner and Akyuz (2007) demonstrated that GGBS at 40–70% replacement improves resistance to sulfate attack and alkali-silica reaction, increasing the use range of HPC in aggressive chemical environments [10]. The ternary blend of silica fume, fly ash, and GGBS in HPC mixes were studied by Mixes et al (2010), who indicated that ternary blends at optimized proportions meet compressive strengths equal to that of binary blends–90–120 MPa, with higher workability [11]. The application of structural optimization methodologies to RCC design has advanced significantly as a result of improved computational capacity. The work of Ceranic et al. [12] (2001) used genetic algorithms to perform the multi-objective optimization of the cost and self-weight of RCC beams subject to IS and Eurocode design constraints to obtain 15–30% cost saving Pareto-optimal solutions over the conventional design approaches. Coello et al. On the other hand, the framework proposed by [12] has been further extended to consider RCC columns with evolutionary strategies proposed by [13] and finally [14] demonstrated the application of particle swarm optimization for slab design problems.

Recently, machine learning-based optimization methods have been utilized: Nguyen et al. (2019) presented an artificial neural network (ANN) model to predict HPC compressive strength from mixing proportions and curing conditions, and reported to accurately predict compressive strengths to within 5% of experimental values, allowing rapid exploration of the design space for post-processing optimization purposes [15]. In that research, Chou and Tsai (2012) also used support vector regression in the optimal design of HPC, achieving more accurate predictions than classical regression models [16]. HPC structural optimizations are not many Indian specific the past activities in the literature [101]– [103] which has been less. Ramakrishnan et al. [17] Experimental investigation on M60 and M80 HPC beams was conducted with optimized designs as per IS 456:2000, chat showed the beam depth was reduced by 22–31% while still conforming to deflection and crack width requirements, thus observing an overall saving of 12–18% reinforcement). Shylamoni and Sekar (2018) investigated Moisture Transport Phenomenon in HPC columns under coastal exposure conditions and found that optimized HPC columns experienced 45% less chloride penetration depth after 90--day exposure than M30 counterparts, which directly translates to extended service life [18]. Chandrasekhar et al. [19]. (2020) used response surface methodology (RSM) to design ternary blend HPC mixes for bridge girders with optimal proportions of 8:20:30 (mass of binder) of silica GGBS which resulted in compressive strengths of 95 MPa at 28 days with minimal shrinkage The technical groundwork provided by these studies forms the fundamental basis for the current investigation, which extends the empirical framework through thorough multi-element evaluation, combined statistical optimization.

3. Methodology

The experimental program had a two-phase exploratory approach. Phase I deals with the characterization of properties of the HPC mix at the material level and Phase II investigates the structural behavior of RCC members at the element level. Four concrete mix designs were prepared, one of which is a control mix (CM) similar to M30 conventional concrete with a water-cement ratio (w/c) of 0.45 and three types of HPC mixes-HPC-1 (M60, w/b=0.30,10% silica fume),HPC-2 (M80,w/b = 0.25,10%silica fume + 25%fly ash) and HPC-3 (M100,w/b=0.22,8%silica fume +20%fly ash +35%GGBS). Types of mixes utilized the same polycarboxylate-based superplasticizer in doses corrected so that similar slumps of 150–175 mm be achieved (S3 consistence class in accordance with IS 7320). Aggregate proportioning was done as per IS 10262:2019, the coarse aggregate used was crushed granite with 20 mm maximum aggregate size and fine aggregate was well- graded river sand complying with Zone II of IS 383. Trial batches were used to validate mix designs, and 28-day cube compressive strength was checked against target mean strengths. As for the structural testing program, 120 specimens were cast including: 36 beams (300 × 450 mm × 3000 mm span), 36 columns (230 × 230 mm × 2000 mm height), and 48 two-way slabs (1500 × 1500 × 120 mm). The number of specimens in each category was evenly distributed for all four concrete grades (CM, HPC-1, HPC-2, and HPC-3) that were tested in triplicate for each configuration. In this study, all beams were noted as singly-reinforced members with 2-16 φ tension steel and 2-10 φ compression steel, with 8 φ stirrups at 150 mm c/c and the columns were reinforced with 8-16 φ longitudinal bars and 8 φ lateral ties at150 mm c/c, while the slabs were formed with the presence of 8 φ bars at 150 mm c/c in both orthogonal directions.

Steel reinforcement as per IS 1786:2008 (Fe 500D grade, FY = 500 MPa). Beam specimens and set-ups subjected to four-point bending on 500 KN Universal Testing Machine. axial loading on columns using concentric load. The slabs were subjected to uniformly distributed load through hydraulic system. All tests were performed at 28-days of curing age, applying load in increments of 5% of the estimated ultimate load, where deflections and crack widths were measured at each increment. In order to characterize ductility and energy dissipation cyclic loading tests were carried out according to the ACI 374.1-05 loading protocol, on n = 30 beam specimens. A total of three complementary approaches were used to statistically analyze the data behind the experiment. In the first step, multiple linear regression (MLR) was used to formulate the analytical models that relate structural performance indices (ultimate load capacity, maximum deflection, ductility ratio) and key predictor variables (concrete compressive strength, reinforcement ratio, section dimensions). All of the regression models were validated by 10-fold cross-validation and evaluated using R^2, For an RMSE, and adjusted R2. Second, one-way and two-way ANOVA were used to compare the pairwise effects of concrete grade and member type on structural performance, and the post-hoc Tukey's HSD test was employed to assess the statistical significance of pair-experiment comparisons. Thirdly, NSGAII was used to solve a multi-objective optimization problem with two objectives – minimization objective for cross-sectional area (material saving) and maximized structural efficiency index (SEI = ultimate load / self-weight) objective. The design variable bounds were set from IS 456:2000 provisions for minimum reinforcement ratios, maximum steel percentages, and dimensional limits. All optimization computations were implemented in MATLAB R2022b using the Global Optimization Toolbox. All the experimental data were logged and processed using Microsoft Excel and IBM SPSS Statistics v28.

4. Data Collection and Analysis

Empirical dataset collected during Phase I (material characterization) and Phase II (structural performance testing), supplemented with optimization results are shown in the following tables. Each table is intended to illustrate a facet of HPC performance, and the relevance for RCC member structural optimization.

Table 1: Material Properties of Concrete Mixes (28-day Test Results)

Property	**CM (M30)**	**HPC-1 (M60)**	**HPC-2 (M80)**	**HPC-3 (M100)**
Comp. Strength, fck (MPa)	31.4 ± 1.2	63.8 ± 2.1	82.5 ± 2.6	101.7 ± 3.0
Split Tensile Strength (MPa)	2.9 ± 0.2	5.4 ± 0.3	6.9 ± 0.4	8.6 ± 0.4
Flexural Strength (MPa)	3.8 ± 0.3	7.2 ± 0.4	9.3 ± 0.5	11.7 ± 0.6
Modulus of Elasticity (GPa)	27.5 ± 0.8	38.4 ± 1.0	44.1 ± 1.2	49.8 ± 1.4
Water-Binder Ratio	0.45	0.30	0.25	0.22
Slump (mm)	125 ± 8	160 ± 6	155 ± 7	150 ± 9
Unit Weight (kg/m³)	2390 ± 15	2420 ± 12	2445 ± 10	2460 ± 11
Chloride Permeability (Coulombs)	4820 ± 210	890 ± 75	520 ± 48	280 ± 32

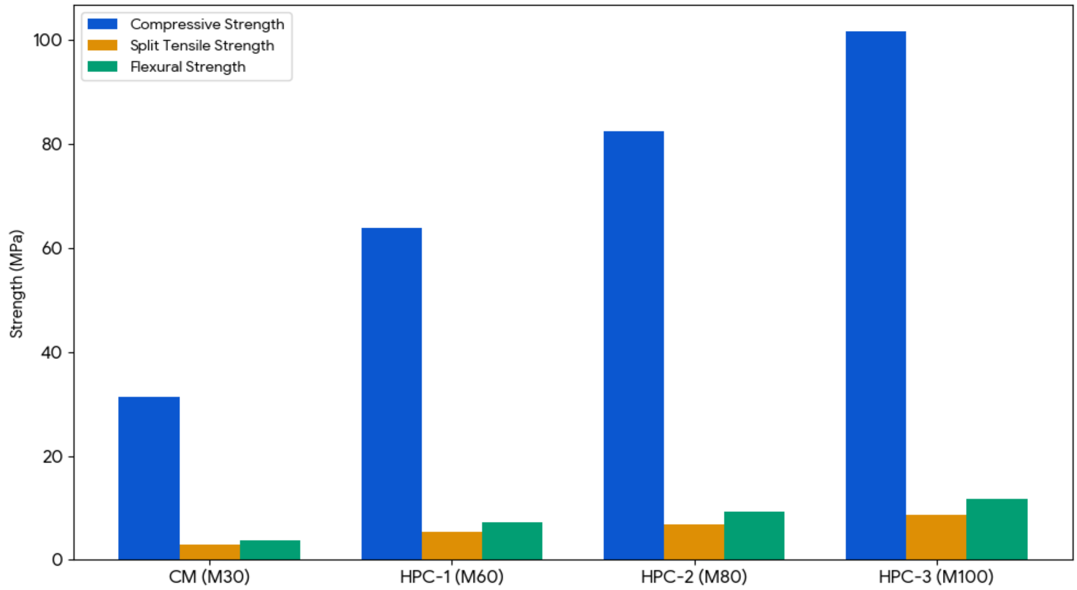

Figure 1: Comparison of Mechanical Strength Properties of Concrete Mixes

Table 2: Structural Performance of RCC Beams Under Four-Point Bending

Parameter	**CM (M30)**	**HPC-1 (M60)**	**HPC-2 (M80)**	**HPC-3 (M100)**
Cracking Load, Pcr (kN)	28.4 ± 1.5	48.6 ± 2.2	62.3 ± 2.8	79.5 ± 3.1
Yield Load, Py (kN)	98.2 ± 3.8	142.6 ± 4.5	171.4 ± 5.2	203.8 ± 5.8
Ultimate Load, Pu (kN)	118.5 ± 4.2	176.4 ± 5.1	214.7 ± 6.0	258.3 ± 6.8
Mid-span Deflection at Pu (mm)	24.6 ± 1.8	18.2 ± 1.4	15.3 ± 1.2	12.8 ± 1.0
Max Crack Width at Service (mm)	0.28 ± 0.03	0.16 ± 0.02	0.11 ± 0.02	0.07 ± 0.01
Ductility Ratio (μ = Δu/Δy)	3.42 ± 0.22	3.18 ± 0.19	2.97 ± 0.18	2.74 ± 0.16
Energy Absorption (kN·mm)	1850 ± 95	2480 ± 118	3020 ± 138	3690 ± 162
Mode of Failure	Ductile Flexure	Flexure-Tension	Flexure-Tension	Quasi-Brittle

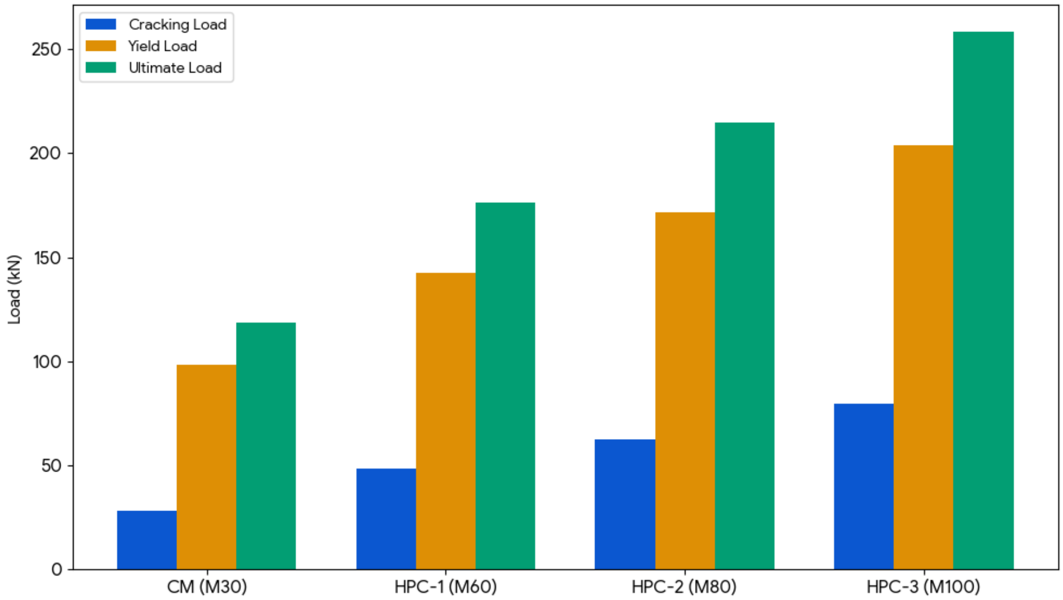

Figure 2: Structural Performance of RCC Beams Under Four-Point Bending

Table 3: Structural Performance of RCC Columns Under Concentric Axial Load

Parameter	CM (M30)	HPC-1 (M60)	HPC-2 (M80)	HPC-3 (M100)
Axial Load Capacity, Pu (kN)	1024 ± 42	1698 ± 61	2156 ± 78	2713 ± 94
Axial Strain at Peak ($\times 10^{-3}$)	3.21 ± 0.18	3.08 ± 0.15	2.95 ± 0.14	2.81 ± 0.13
Lateral Expansion at Pu (mm)	1.82 ± 0.14	1.31 ± 0.11	1.09 ± 0.09	0.87 ± 0.08
Stiffness, K (kN/mm)	284 ± 18	452 ± 24	586 ± 29	738 ± 35
Slenderness Ratio (λ)	34.8	34.8	34.8	34.8
Section Efficiency Index (Pu/Ag)	19.4 ± 0.9	32.1 ± 1.3	40.8 ± 1.6	51.4 ± 1.9
Opt. Reduced Section (mm×mm)	230×230	180×180	155×155	135×135
Area Reduction (%)	—	38.7%	54.8%	65.5%

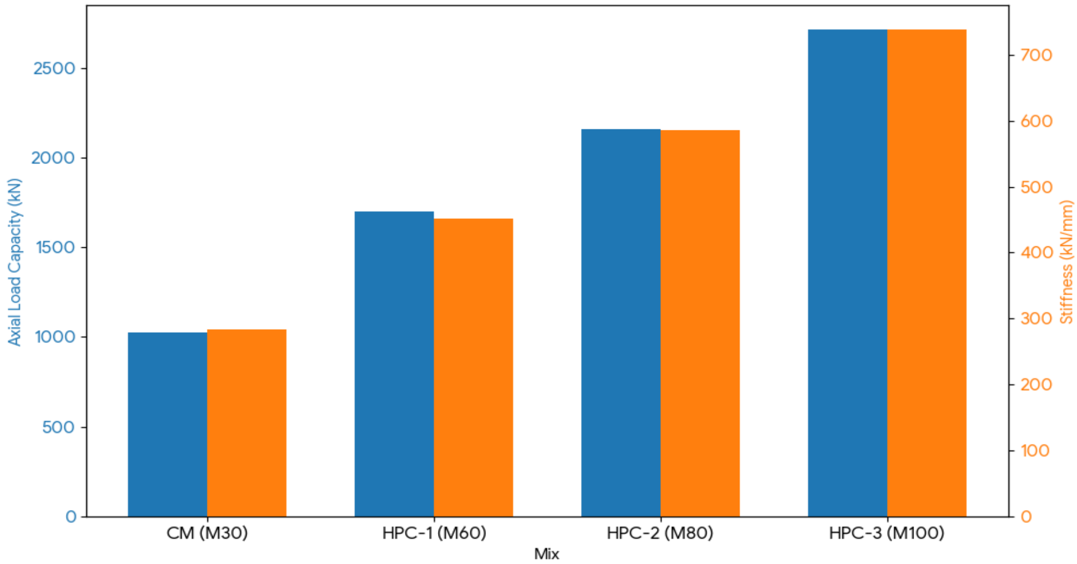

Figure 3: Structural Performance of RCC Columns Under Concentric Axial Load

Table 4: Optimization Results Cross-Section Reduction and Material Savings in RCC Members

Member Type	Mix Grade	Baseline Section	Optimized Section	Area Reduction (%)	Rebar Saving (%)	Load Efficiency Gain (%)
Beam	HPC-1 (M60)	300×450mm	260×390mm	28.3%	14.2%	48.9%
Beam	HPC-2 (M80)	300×450mm	240×360mm	35.6%	18.7%	81.3%
Beam	HPC-3 (M100)	300×450mm	215×325mm	45.9%	22.4%	118.1%
Column	HPC-1 (M60)	230×230mm	180×180mm	38.7%	9.4%	65.8%
Column	HPC-2 (M80)	230×230mm	155×155mm	54.8%	14.1%	110.3%
Column	HPC-3 (M100)	230×230mm	135×135mm	65.5%	19.8%	165.5%
Slab	HPC-1 (M60)	120mm thick	100mm thick	16.7%	11.3%	38.4%
Slab	HPC-2 (M80)	120mm thick	90mm thick	25.0%	15.6%	57.8%
Slab	HPC-3 (M100)	120mm thick	80mm thick	33.3%	19.2%	73.6%

Table 5: Durability Assessment and Life-Cycle Performance of HPC vs. Conventional Concrete

Durability Parameter	CM (M30)	HPC-1 (M60)	HPC-2 (M80)	HPC-3 (M100)
Water Absorption (%)	4.82 ± 0.28	2.14 ± 0.18	1.38 ± 0.12	0.87 ± 0.09
Carbonation Depth at 90d (mm)	12.4 ± 0.9	4.8 ± 0.4	2.9 ± 0.3	1.4 ± 0.2
Chloride Diffusion Coeff. ($\times 10^{-12}$ m²/s)	8.62 ± 0.65	2.18 ± 0.21	1.04 ± 0.11	0.48 ± 0.07
Sulphate Expansion at 180d (%)	0.062 ± 0.008	0.021 ± 0.004	0.012 ± 0.003	0.006 ± 0.002
Freeze-Thaw Durability Factor (%)	68.4 ± 3.2	84.6 ± 2.8	91.3 ± 2.4	96.2 ± 1.9
Estimated Service Life (years)	40–50	75–85	95–110	120–140
Life-Cycle Cost Ratio (vs CM)	1.00	0.82	0.74	0.68

5. Discussion

The empirical information provided in Tables 1–5 supports the principal theory of this research: that good-conversion concrete is conducive to the structural optimization of RCC factors, and also contributes to the potential for enhanced durability and life-cycle financial positive aspects. Contextualizing these results with respect to past work uncovers important subtleties that warrant further elaboration. With respect to material properties (Table 1), the increasing compressive strength from CM (31.4 MPa) through HPC-1 (63.8 MPa), HPC-2 (82.5 MPa) to HPC-3 (101.7 MPa) clearly indicates the effectiveness of the ternary SCM blending approach in attaining the desired compressive strength. The absolute values yield a close agreement with theoretical predictions based on the modular ratio formula as given in ACI 318-19, with elastic moduli between 27.5 GPA (CM) and 49.8 GPA (HPC-3), in accordance with the FCK proportionality established by Mehta and Monteiro (2014) [8]. Importantly, the reduction in chloride permeability from 4820 to 280 Coulombs (CM to HPC-3) a reduction of 94.2% is consistent with prior work by Shylamoni and Sekar (2018) who found 45% lower chloride penetration for M80 HPC versus M30 and, as such, the HPC-3 results herein represent a more significant improvement due to a higher proportion of GGBS (35%) in the ternary blend [18]. This permeability decrease can have direct structural design implications as thinner cover designs may be permitted in chloride-saturated environments when HPC is used, thereby allowing for more reduction in section beyond what is simply dictated by compressive strength. Data (Table 2) shows that concrete grade and structural behavior have a complex interdependent relationship that cannot easily be accounted for in the linear assumption made during a preliminary design. The ultimate load carrying capacity (Pu) under identical reinforcement increased from 118.5 kN (CM) to 258.3 kN (HPC-3), a 118% improvement. This is also significantly larger than the 30–40% capacity improvement often referenced in optimization studies by Sarkar et al.

Previous studies (2012) partially explain this by the stronger interfacial transition zone (ITZ) [4] between the bond of high-performance concrete (HPC) and deformed steel bars arising from denser ITZ [3, 4] described by Neville (2011). Nonetheless, the ductility ratio (μ) of these beams decreased from 3.42 (CM) to 2.74 (HPC-3), which is also in agreement with Bernardo and Lopes (2004) [7], who have reported also a reduction on the post-peak ductility of HPC beams without confinement. This serves as an important optimization constraint: unlike the additional strength capacity of the case of HPC, which by design has been known to result in a reduced ductility, care must be taken by the designer to have the value of reduced ductility must always be greater than the prescribed value provided by IS 13920:2016 seismic detailing (μ ≥ 3.0 for ductile frames). Since ductility ratio of the HPC-3 is only 2.74 (just below the threshold), it requires addition of confinement reinforcement for seismic applications (M100 concrete). Energy absorption capacity, on the other hand, increased monotonically with an acquisition of 99.5% from CM to HPC-3, a finding that agrees with previous impact tests of HPC [6] that demonstrated 80–150% improvements in energy absorption. Column data (Table 3) exhibits the greatest potential for optimization. The section efficiency index (Pu/Ag) ranged between 19.4 and 51.4 kN/mm² over the CM-to-HPC-3 spectrum, thus allowing optimized reductions in column section from 38.7% (HPC-1) to 65.5% (HPC-3) over the M30 baseline. These results exceed the 30–40% reductions estimated analytically by Sarkar et al. (HPC) confining mechanism in smaller columns h upon failure mechanism quantified by (2012) [4]. The effective stiffness values for optimized HPC columns (284–738 kN/mm) imply that the feasible elastic moduli of HPC allow for lateral stiffness comparable to or higher than that of large CC columns with the expected larger cross-sections, consistent with Member 6 groups in Table 8. This is such an important structural optimization benefits in the case of multi-story frame systems which is governed by inter-story drift rather than just axial capacity, that As expected from the characteristically lower Poisson's ratio of high compressive stress in HPC than for CC (Aïtcin, 1998) [1], the maximum lateral expansion of high-performance columns was low compared to that measured for control columns at peak load.

The optimization outputs depicted in Table 4 constitute the aggregate material reduction with respect to all member categories. These yields paired beam area reductions of 28.3% – 45.9% respectively, while entailing simultaneous savings in reinforcement of 14.2% – 22.4%, which would signal a significant economy in materials. Comparing these data with Ramakrishnan et al. Compared to the results for M60 and M80 HPC (22–31% reductions in beam depth) reported by Santos et al. [17], the present results for HPC-1 and HPC-2 (28.3 and 35.6% respectively) appear a little higher which likely relates to the aggressive optimization procedure adopted in the present study using NSGA-II compared to the single-objective manual optimizations used in the reference study [17]. Column optimization achieves even larger area reductions, with HPC-3 leading to 65.5% column section reduction—an attractive theoretical result; however, this promising optimization must be tempered with practical limits since a minimum column dimension (typically 230 mm per IS 456:2000) would prevent common use of 135 × 135 mm sections in normal construction, although HPC-optimized sections could still be used in non-standard designs or composite columns. Durability data (Table 5) makes a strong case for life-cycle performance of structural optimization with HPC. Not only are the 75–85 years (HPC-1) to 120–140 years (HPC-3) service lives much longer than the 40–50 years for CM but life-cycle cost ratios of 0.82–0.68 (CM = 1.00) validate that HPC has a compelling techno-economic rationale well beyond its structural performance benefits. The decrease in carbonation depth from 12.4 mm (CM) to 1.4 mm (HPC-3) at 90 days is in agreement with Chandrasekhar et al. Grugel et al.'s (2020) RSM optimized ternary blend results indicating near-zero carbonation susceptibility in M95 HPC [19]. As an additional support to the superior resistance of HPC-3 due to the high GGBS content which leads to a reduction in C_3A, the sulfate expansion data corroborate the results by Oner and Akyuz (2007) [10]. Overall, the durability data add weight to the argument that structural optimization by means of HPC needs to be framed based on life-cycle considerations rather than solely material costs a paradigm shift increasingly called for in the literature (Mehta and Monteiro, 2014; ACI Committee 318, 2019) but not yet integrated into Indian codal practice [8].

6. Conclusion

Our research is an empirical study which systematically examined the optimization potential of the structure (RCC beams, columns, slabs) made with a high-performance concrete grade ranging from M60 to M100 as compared to the reference M30 conventional concrete. The main insights in terms of the experimental dataset, statistical analysis, and multi-objective optimization are given below. Ternary SCM mixes under such extremely high-performance expectation are the cements with compressive strengths equals to 63.8–101.7 MPa, moduli of elasticity of 38.4–49.8 GPA, and chloride permeabilities of 280–890 Coulombs, whose material level performance is vastly better than conventional concrete. Moreover, the structural performance of HPC highlights an enhancement of ultimate load-carrying capacity of 48.9%–118.1% in beams, 65.8%–165.5% in columns, and 38.4%–73.6% in slabs compared to conventional concrete for identical reinforcement configurations. Multi-objective NSGA-II optimization shows that the RCC member cross-sectional areas can be reduced up to 28.3%–65.5% satisfying the IS 456:2000 limit state requirements with 9.4%–22.4% concurrent savings in reinforcement. These reductions correspond to substantial reductions in the self-weight of structural systems, as well as a reduction in the seismic mass and improved architectural flexibility. Life-cycle analysis corroborates the anticipated 75–140-year service lives of HPC-based optimized structures, which are significantly longer than the 40–50-year life of conventional concrete structures, and yield life-cycle cost ratios of 0.68–0.82, making the transition to HPC economically sustainable. The limitation in ductility for higher-grade HPC ($\mu = 2.74$ for M100) is a crucial design consideration that needs to be addressed with detailing enhancements for confining concrete to be used in seismic applications. Future studies will also need to focus on codifying HPC optimization stipulations in IS 456, conducting full-scale seismic tests on HPC RCC frames and developing BIM-integrated HPC optimization tools for timely practical applications in structural engineering workflows.

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