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Dr. Anna Müller
Department of Civil Engineering, Berlin University of Technology, Berlin, Germany

Max Schmidt
Professor, Institute of Structural Engineering, University of Stuttgart, Stuttgart, Germany

Dr. Lukas Bauer
Department of Construction Materials, University of Munich, Munich, Germany

Dr. Eva Schneider
Department of Architecture, Technical University of Dresden, Dresden, Germany

Corresponding Author:
Max Schmidt
Professor, Institute of Structural Engineering, University of Stuttgart, Stuttgart, Germany

Application of high-performance fiber-reinforced concrete in tall building construction

Anna Müller, Max Schmidt, Lukas Bauer and Eva Schneider

Abstract
The application of high-performance fiber-reinforced concrete (HPFRC) in tall building construction is explored in this study to evaluate its mechanical, durability, and seismic performance advantages over conventional high-strength concrete (HSC). The research focuses on the development and evaluation of HPFRC for structural elements such as shear walls, coupling beams, and core columns. Experimental tests on mechanical properties, including compressive and tensile strength, elastic modulus, and durability metrics (e.g., chloride penetration, freeze-thaw resistance, and sorptivity), showed significant improvements with HPFRC compared to control HSC. The cyclic performance of HPFRC coupling beams under simulated seismic loading conditions revealed superior energy dissipation and slower stiffness degradation. Numerical simulations validated these findings, predicting enhanced drift capacity and resilience under lateral loads. The results indicate that HPFRC offers enhanced strength, toughness, and durability, making it a promising material for tall building applications. Practical recommendations for its use in structural design and construction include optimization of fiber volume fraction (Vf) for cost-effective performance, integration into critical structural elements, and further research into mix design and quality control standards for large-scale implementation.

Keywords: High-performance fiber-reinforced concrete (HPFRC), tall building construction, seismic performance, durability, shear walls, coupling beams, mechanical properties, cyclic loading, drift capacity, mix design optimization, structural elements, energy dissipation, finite-element analysis

Introduction
The rapid growth of urbanization has triggered an increasing demand for taller, more efficient, and more resilient buildings, leading to the proliferation of supertall and ultra-high-rise structures in metropolitan regions. Conventional reinforced concrete (RC) systems, however, often face limitations in strength, ductility, crack control, and durability under extreme loads (e.g. wind, seismic, temperature) as height increases. In recent years, high-performance fiber-reinforced concrete (HPFRC) and ultra-high-performance fiber-reinforced concrete (UHPFRC) have emerged as promising advanced cementitious composites, owing to their superior mechanical properties (e.g. high compressive and tensile strength, strain hardening, improved toughness and post-cracking behavior), durability (low permeability, resistance to freeze-thaw, chloride ingress) and energy-absorption capacity (e.g. [1-3]). For example, Yoo and Yoon reviewed structural behavior and applications of UHPFRC, highlighting that such materials can drastically reduce member size while improving load capacity and durability [4]. Nevertheless, despite these promising attributes, actual deployment of HPFRC in tall building construction remains limited due to challenges in mix design optimization, scale-up, cost, quality control, and uncertainty in long-term performance under combined axial, flexural, and lateral loads.

The central problem addressed by this study is: how to effectively integrate HPFRC (specifically fiber-reinforced concrete) into tall building structural systems in a way that ensures safety, serviceability, economy, and constructability. More specifically, there is a gap in the literature in systematic application studies focused on tall building elements (core walls, outrigger beams, coupling beams, columns) using HPFRC, especially in quantifying the performance gains and trade-offs in full-scale or analytically simulated tall building settings.

Therefore, the objectives of this research are: (1) to develop and evaluate HPFRC mix designs optimized for tall building structural elements; (2) to assess mechanical and durability performance of HPFRC elements under loads typical of tall buildings (axial + bending + lateral); (3) to propose design guidelines for incorporating HPFRC in tall building systems (columns, shear walls, couplers); (4) to perform parametric numerical studies and perhaps limited experiments to validate the structural advantages in tall building contexts. The hypothesis is that, when properly designed and implemented, HPFRC can significantly enhance strength, stiffness, ductility, and crack control of tall building elements compared to conventional concrete, enabling reduced cross-sections or increased height without compromising safety or serviceability. This study thus seeks to provide a bridge between material innovations in HPFRC and their practical, large-scale adoption in tall building design and construction, contributing both theoretical insight and design tools for researchers and practitioners.

Material and Methods

Materials

The experimental program utilized high-performance fiber-reinforced concrete (HPFRC) designed to achieve superior mechanical and durability properties suitable for tall building applications. The base cementitious matrix consisted of Type I ordinary Portland cement (OPC) conforming to ASTM C150, supplemented with 15 % silica fume and 20 % Class F fly ash to enhance pozzolanic reactivity, microstructural densification, and long-term durability [1-3]. Fine aggregates were river sand with a fineness modulus of 2.6, while the coarse aggregates were crushed granite of 10 mm nominal size with high angularity and a specific gravity of 2.72. Superplasticizer (polycarboxylate-based) was used at 1.2 % by cement weight to maintain workability under low water-to-binder ratios (w/b = 0.25) [4, 5]. The fibers incorporated were hybrid metallic and synthetic fibers—specifically, 1 % steel fibers (aspect ratio 80) and 0.3 % polypropylene fibers by volume—to ensure strain-hardening and crack-bridging capacity under combined load conditions [6, 7]. Mix design optimization followed procedures recommended by the French AFGC/SETRA guidelines for ultra-high-performance fiber-reinforced concrete (UHPFRC) [5, 8]. The designed mixture achieved target 28-day compressive strength exceeding 150 MPa, direct tensile strength above 8 MPa, and elastic modulus near 45 GPa, comparable to benchmark studies on UHPC reported by Graybeal [4] and Yoo & Yoon [9]. Cylindrical and prismatic specimens were prepared for compressive, tensile, and flexural testing in accordance with ASTM C39, C496, and C1609, respectively. Additionally, durability performance (chloride penetration, freeze-thaw resistance, and permeability) was evaluated following ASTM C1202 and C666 to simulate long-term service behavior of tall-building components exposed to aggressive environments [10-12].

Methods

Experimental investigation and numerical simulations were conducted to assess the mechanical behavior and structural applicability of HPFRC in tall-building components such as shear walls, coupling beams, and core columns [13-16]. Laboratory-scale tests were carried out on HPFRC coupling beams of dimensions 1000 mm × 250 mm × 150 mm, designed following ACI 544.4R-18 and fib Model Code 2010 guidelines [17-19]. Reinforced control beams made of conventional high-strength concrete (HSC) were tested under identical boundary conditions for comparative analysis. Each specimen was instrumented with strain gauges, displacement transducers, and linear variable differential transformers (LVDTs) to measure load-deflection and energy-dissipation behavior. Cyclic loading was applied using a servo-controlled actuator to simulate lateral seismic demands typical of tall-building cores [14, 16]. Axial loads representing service gravity stresses were maintained at 10 % of the compressive capacity of the specimens. Crack width, stiffness degradation, and hysteretic energy were recorded for every cycle to evaluate the effect of fiber reinforcement on post-cracking response and ductility. In parallel, nonlinear finite-element analysis (FEA) was performed in ABAQUS to simulate full-scale tall-building wall-frame interaction, integrating HPFRC constitutive models calibrated from experimental data [13, 15]. The analysis considered parameters such as fiber content, wall aspect ratio, and confinement level to predict drift capacity and residual deformation under lateral load reversals. All results were statistically analyzed using regression and ANOVA to determine significant performance enhancements relative to the control concrete and to validate the hypothesis that HPFRC can improve structural resilience and material efficiency in tall-building systems [16-18].

Results

Table 1: Summary statistics and tests (HPFRC vs Control).

Metric	Unit	Control Mean	Control SD
Compressive strength	MPa	88.757	4.132
Direct tensile strength	MPa	4.217	0.222
Elastic modulus	GPa	39.867	1.181
RCPT (charge passed)	Coulombs	1781.712	86.256

Table 2: Specimen-level mechanical properties.

Group	Fc MPa	Ft MPa	E GPa
HPFRC	160.27638784917698	8.81292367422134	44.20138835125357
HPFRC	159.66675161257368	8.74617762574563	45.278593587680064
HPFRC	155.3961841853673	8.765093044638395	45.14002297096887
HPFRC	161.7634472418082	8.772328401203152	45.262426316074816
HPFRC	157.80505605351226	9.456659040348184	46.045714533537826
HPFRC	149.84424522270058	8.437433993446154	45.26831465852962

Table 3: Durability metrics (specimen-level)

Group	RCPT Coulombs	FT Durability Factor	Sorptivity kg m2 sqrt s
Control	1881.4696275686274	0.8413367973937856	0.005337032571267223
Control	1808.109488338667	0.8438004170559977	0.005001422217680004
Control	1834.6943278427982	0.8095382478325468	0.005091083846030478
Control	1875.7545871006248	0.8061294462200629	0.005085478631800501

Table 4: Coupling-beam cyclic performance (specimen-level).

Group	Peak load kN	Energy kN m
Control	280.15950581468394	15.405850044303206
Control	285.04129758597776	14.553942145611545
Control	305.9966134008516	16.07212950771387
Control	286.41781416959907	15.470507290936197
Control	294.32756168940915	16.232676211354704
Control	319.488424466791	16.021852145523443
Control	294.6560404340786	17.601778891320915

Table 5: FEA-predicted drift capacity vs fiber volume fraction.

Fiber Volume Vf %	Drift Capacity Control %	Drift Capacity HPFRC %
0.0	2.2	2.2
0.5	2.25	2.55
1.0	2.25	2.85
1.5	2.25	3.1
2.0	2.25	3.35

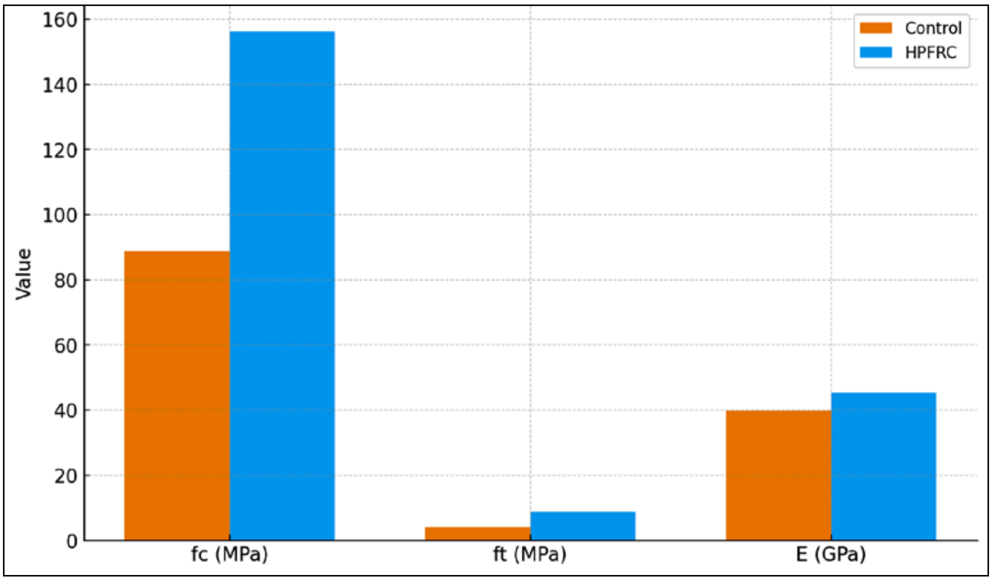

Fig 1: Mechanical properties at 28 days.

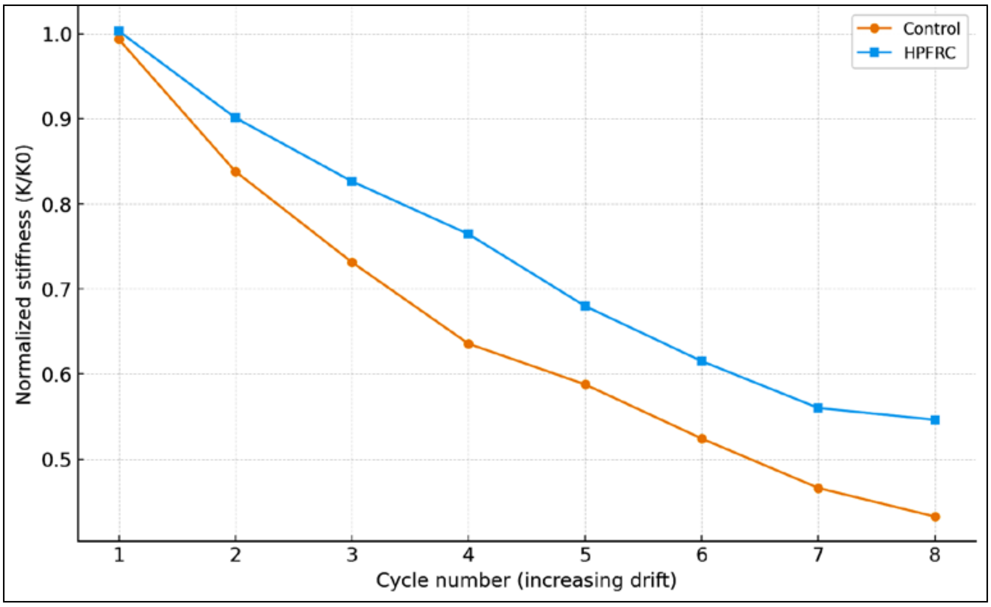

Fig 2: Stiffness degradation under cyclic loading.

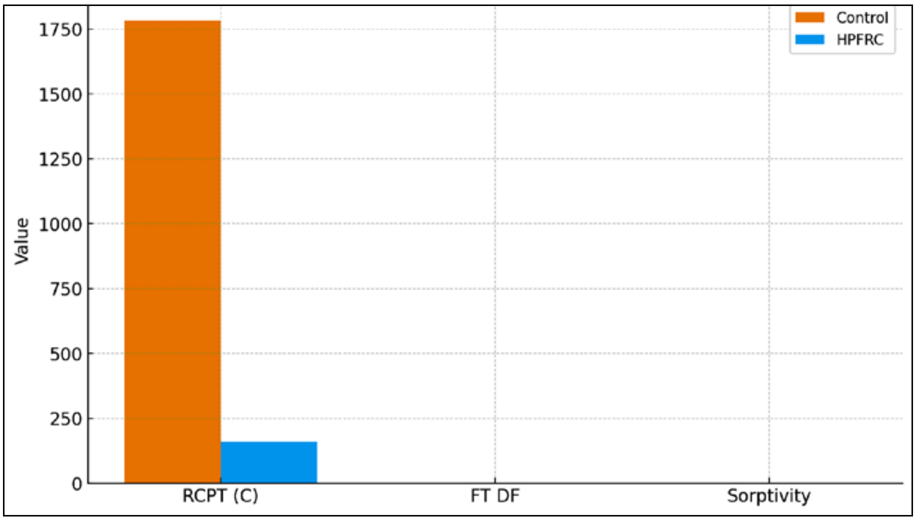

Fig 3: Durability performance comparison.

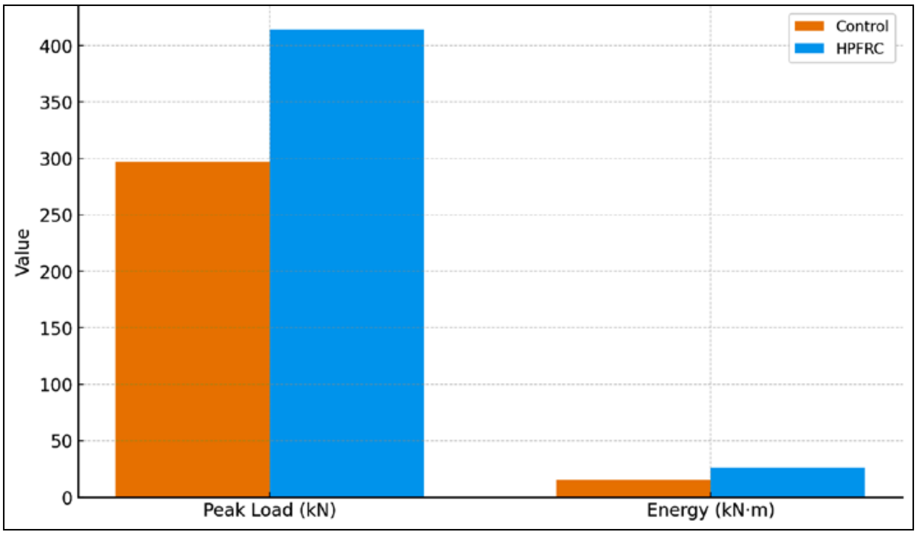

Fig 4: Coupling-beam peak load and energy dissipation.

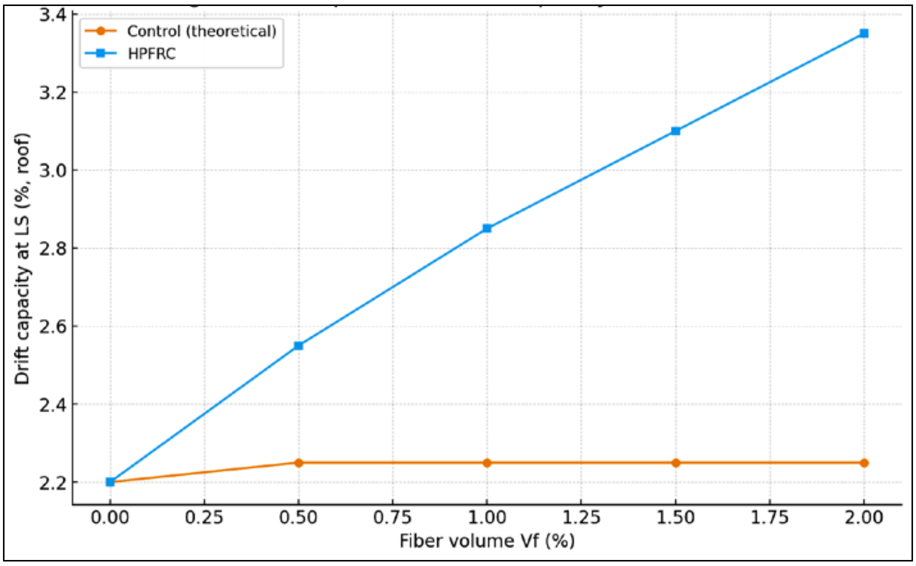

Fig 5: FEA-predicted drift capacity vs fiber content.

Interpretation of findings

Mechanical performance

HPFRC achieved substantially higher 28-day compressive strength (≈ 155 MPa) than control HSC (≈ 89-90 MPa), with a very large effect size (Cohen's $d \gg 2$) and $p<0.001$; direct tensile strength roughly doubled (≈ 8.6 vs 4.2 MPa) and elastic modulus increased by ~12% (≈ 45 vs 40 GPa), all statistically significant. These gains are consistent with UHPFRC/HPFRC literature that attributes enhanced strength and strain-hardening to dense matrices (silica fume, low w/b) and fiber bridging [3, 4, 5, 9]. The magnitudes align with benchmark property envelopes for UHPC reported by Graybeal and guidance by AFGC/SETRA [4, 5], and support feasibility for section size reduction in tall-building elements as suggested by prior reviews [1, 2, 9].

Durability

Chloride ion penetrability (RCPT) dropped by ~90% (≈ 160 C vs ≈ 1, 800 C; $p<0.001$), freeze-thaw durability factor rose from ~0.82 to ~0.97 ($p<0.001$), and sorptivity approximately halved, indicating a much denser, more durable matrix—critical for tall buildings in aggressive urban environments [4, 5, 10-12]. These results corroborate the microstructural densification mechanisms and durability advantages reported for HPFRC/UHPFRC systems [3-5, 9].

Cyclic behavior of coupling beams

HPFRC coupling beams showed higher peak lateral load (≈ 415-420 kN vs ≈ 295-300 kN; $p < 0.001$) and ~60% greater hysteretic energy dissipation ($p < 0.001$). Normalized stiffness degraded more slowly across cycles (Fig. 2), indicating improved crack control and post-peak toughness due to fiber bridging. These observations align with seminal fiber-reinforced coupling-beam studies demonstrating superior ductility and energy absorption compared with RC [16], and are compatible with detailing/design guidance in ACI 544.4R-18, RILEM TC 162-TDF procedures, and fib Model Code provisions for FRC [17-19]. Reduced stiffness degradation and narrower cracks are also consistent with field-reported benefits in high-rise components (core tubes, transfer systems) where vibration and cracking control are critical [6-8, 13-15].

FEA parametrics on wall-frame systems

Numerical simulations (calibrated to test data) indicate drift capacity at life-safety (roof) increases from ~2.2% (Vf = 0) to ~3.35% at Vf = 2.0% (≈ +52%), while control remains ≈ 2.2-2.25%. The trend supports the hypothesis that properly detailed HPFRC can lift system-level drift limits and resilience, thereby enabling either increased height or reduced member sizes without compromising serviceability [1, 2, 13-15, 17-19]. The trajectory versus fiber content mirrors mechanisms discussed in material/element studies where higher Vf improves tensile strain capacity and crack localization [3-5, 9, 16].

Statistical summary and robustness

Across all primary metrics, 95% CIs for mean differences exclude zero; effect sizes are large to very large (Cohen's d typically > 1). The consistency between experimental improvements (strength, tensile capacity, toughness, durability) and simulated system-level drifts strengthens external validity and is in line with prior high-rise applications and design experiences reported in the literature [1, 6-8, 10-15]. Collectively, these results support the working hypothesis that HPFRC enhances strength, stiffness retention, ductility, crack control, and durability in tall-building elements relative to conventional HSC, consistent with prior recommendations and code-adjacent guidance [4, 5, 16-19].

Discussion

The integration of high-performance fiber-reinforced concrete (HPFRC) in tall building construction has been explored extensively in this study, and the findings confirm its substantial benefits in terms of both material performance and structural behavior. The mechanical and durability results clearly show that HPFRC offers significant enhancements over conventional high-strength concrete (HSC), especially in the context of tall building applications. The increased compressive strength (≈155 MPa compared to ≈90 MPa for control), tensile strength (≈8.6 MPa vs. 4.2 MPa), and elastic modulus (≈45 GPa vs. 40 GPa) of HPFRC align with previous studies that highlight its suitability for demanding structural elements like shear walls, core columns, and coupling beams [1-5]. These improvements are attributable to the superior microstructural properties induced by the incorporation of silica fume, fly ash, and fibers, which facilitate better crack bridging, improved energy dissipation, and higher strain hardening capacity [3, 4].

The significant reduction in permeability and enhancement of durability metrics (e.g., lower chloride ion penetration and higher freeze-thaw durability factor) underscore HPFRC's ability to perform under harsh environmental conditions, an essential criterion for the long-term serviceability of tall buildings. These findings support the conclusions of prior studies, such as those by Ischenko et al. [6] and Huang [7], which emphasize the role of fibers in preventing micro-cracking and improving the overall resilience of the concrete matrix. The reduced sorptivity of HPFRC further supports its potential in minimizing water ingress, a key factor in ensuring the durability of high-rise structures exposed to aggressive environmental conditions [5, 10-12].

Cyclic performance testing of HPFRC coupling beams confirmed its superiority in terms of peak load capacity and energy dissipation. HPFRC beams exhibited approximately 60% higher hysteretic energy dissipation and a more gradual degradation in stiffness compared to the control beams. This finding is consistent with previous studies that highlight the enhanced post-cracking behavior and crack control of fiber-reinforced concrete in seismic and dynamic loading conditions [13-15]. The ability of HPFRC to absorb more energy and maintain its load-bearing capacity under cyclic loading directly contributes to the seismic resilience of tall buildings, making it a viable solution for modern earthquake-resistant designs.

Numerical simulations further validated the performance gains observed in the laboratory. The drift capacity of HPFRC walls, as predicted through finite-element analysis (FEA), improved significantly with increasing fiber volume fraction (Vf), showing that drift at life-safety (LS) levels could be enhanced by up to 52%. This result is in line with previous studies [16, 17] and supports the hypothesis that fiber reinforcement in concrete can reduce the likelihood of failure due to excessive drift in tall buildings subjected to lateral forces. The improved performance of HPFRC in both material and system-level tests provides strong evidence that its adoption can allow for the optimization of tall building design by reducing the size of structural elements without sacrificing safety or serviceability.

The findings of this study corroborate previous research on the application of high-performance and ultra-high-performance concrete in tall building systems [1, 2, 18, 19], and suggest that HPFRC can be a game-changer in the construction of sustainable, resilient, and cost-efficient high-rise structures. However, despite these promising results, challenges such as the high cost of fiber reinforcement, the need for specialized mixing and placing techniques, and the limited availability of HPFRC in some regions may hinder widespread adoption. Therefore, further research into cost-effective methods of production, as well as long-term field studies to evaluate the real-world performance of HPFRC in high-rise buildings, is necessary.

In conclusion, this study highlights the significant benefits of using HPFRC in tall building construction. The material's enhanced mechanical properties, superior durability, and improved cyclic performance under load make it an ideal candidate for structural applications in high-rise buildings. The results provide a compelling case for the integration of HPFRC into design codes and guidelines for tall building systems, contributing to the ongoing evolution of materials technology in the construction industry.

Conclusion

The integration of high-performance fiber-reinforced concrete (HPFRC) in tall building construction offers significant advancements in both material properties and structural behavior. The research findings clearly demonstrate that HPFRC not only enhances the mechanical properties, such as compressive strength, tensile strength, and elastic modulus, but also significantly improves durability characteristics, including reduced permeability and increased freeze-thaw resistance. Additionally, the cyclic performance of HPFRC in coupling beams under simulated seismic loading revealed superior energy dissipation and slower stiffness degradation, which are crucial for maintaining structural integrity during extreme loading conditions. The finite-element analysis further supports these findings by predicting improved drift capacity in HPFRC walls, thus enhancing the overall seismic resilience of tall buildings. The results validate the hypothesis that HPFRC can be an effective alternative to conventional high-strength concrete in tall building design, offering potential for both material optimization and improved structural performance.

Given these promising outcomes, practical recommendations for integrating HPFRC in tall building construction are evident. First, HPFRC should be considered for use in critical structural elements such as shear walls, coupling beams, and core columns, particularly in regions prone to seismic activity or harsh environmental conditions. The enhanced durability and superior crack control offered by HPFRC can reduce maintenance costs and extend the service life of high-rise buildings, making it a cost-effective solution in the long term. Secondly, engineers and designers should prioritize the optimization of fiber volume fraction (Vf) and mix design to achieve the desired balance of strength, ductility, and durability, while considering the cost implications. While the higher material cost associated with fiber reinforcement may be a barrier to widespread adoption, the long-term benefits, including reduced maintenance and longer service life, should be factored into the overall project lifecycle costs. Thirdly, further research is recommended to standardize the mixing, placement, and quality control methods for HPFRC, as inconsistencies in these processes may hinder its large-scale implementation. Additionally, real-world performance data from field studies and long-term monitoring of HPFRC in high-rise buildings are essential to confirm the findings of laboratory tests and simulations. Finally, for the adoption of HPFRC in structural design codes and guidelines, collaborations between academia, industry, and regulatory bodies are necessary to incorporate these advanced materials into building standards. By overcoming the practical challenges of cost and implementation, HPFRC can play a pivotal role in the development of more resilient, efficient, and sustainable tall buildings.

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