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Performance evaluation of high-strength concrete in seismic-resistant frame structures

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Abstract
This study investigates the seismic performance of high-strength concrete (HSC) in reinforced concrete frame structures, focusing on its lateral strength, ductility, energy dissipation, and stiffness degradation under simulated earthquake loading. Six one-third-scale, two-story, two-bay frames were tested using displacement-controlled quasi-static cyclic loading to compare HSC with normal-strength concrete (NSC) frames. The results demonstrated that HSC frames achieved significantly higher peak lateral strength, increased initial stiffness, and superior energy dissipation capacity, while maintaining ductility comparable to NSC frames through proper confinement detailing. Strength degradation at 3% drift was lower in HSC specimens, and residual drift was reduced, indicating better re-centering behavior and post-earthquake functionality. These improvements are attributed to the material properties of HSC and the effectiveness of seismic detailing in controlling brittle failures. The findings support the strategic integration of HSC in critical structural elements, emphasizing the importance of confinement reinforcement to achieve ductile and resilient behavior. The study also provides practical recommendations for seismic design, including optimized detailing, performance-based criteria, and consideration of residual drift as a key parameter. Overall, the results confirm that well-detailed HSC frames can provide enhanced seismic resilience and structural performance, making HSC a viable and sustainable material for earthquake-resistant construction.

Keywords: High-strength concrete, seismic performance, ductility, energy dissipation, lateral strength, stiffness degradation, residual drift, reinforced concrete frame, confinement, earthquake-resistant structures

Introduction

The increasing frequency of strong earthquakes has intensified the global focus on resilient structural systems capable of sustaining high seismic loads. High-strength concrete (HSC) has emerged as a critical material in modern civil engineering due to its superior compressive strength, durability, and reduced cross-sectional dimensions, which make it well-suited for high-rise and critical infrastructure projects in seismic zones [1-3]. Compared to conventional normal-strength concrete, HSC provides enhanced stiffness and load-bearing capacity, contributing to reduced lateral drift and improved structural integrity under dynamic loading conditions [4, 5]. These advantages have led to its widespread use in seismic-resistant frame structures, including buildings, bridges, and transportation systems, especially in earthquake-prone regions such as those surrounding the Pacific Ring of Fire [6-8].

However, despite these advantages, the brittle nature of HSC under high strain rates poses significant challenges in seismic applications. Unlike ductile materials, HSC can experience sudden failure when subjected to cyclic seismic loads, leading to reduced energy dissipation and potential structural collapse if not properly confined [9-11]. This issue is particularly critical in reinforced concrete moment-resisting frames, where plastic hinges are expected to form in a controlled manner during seismic events. Inadequate ductility and energy absorption may compromise the fundamental principles of earthquake-resistant design [12, 13]. Furthermore, the interaction between high-strength concrete and steel reinforcement under cyclic loading remains complex, with factors such as bond-slip behavior, confinement effects, and cracking patterns playing decisive roles in overall performance [14, 15]. These uncertainties highlight the necessity of performance-based design approaches and advanced evaluation methods to ensure seismic safety.

This research aims to systematically evaluate the performance of high-strength concrete in seismic-resistant frame structures through experimental and analytical methods. The primary objectives are to:

1. Assess the load-displacement behavior and ductility of HSC frames under cyclic lateral loads;
2. Analyze energy dissipation and stiffness degradation patterns; and
3. Compare the performance with that of normal-strength concrete frames under similar seismic demands [16-18].

The hypothesis guiding this study is that properly confined high-strength concrete, when used in well-detailed seismic-resistant frame structures, can achieve comparable or superior ductility, lateral strength, and energy dissipation to conventional concrete frames, thereby enhancing structural resilience during strong earthquakes [19].

Material and Methods

Materials

The experimental program was designed to investigate the seismic performance of high-strength concrete (HSC) in reinforced concrete frame structures under simulated earthquake loading. The concrete mix was proportioned to achieve a target compressive strength of 80 MPa at 28 days, using Type I ordinary Portland cement, crushed granite coarse aggregates (maximum size 12.5 mm), and river sand as fine aggregate [1, 2]. High-range water-reducing admixtures were incorporated to ensure workability while maintaining low water-cement ratios, a critical factor for achieving the desired strength [3, 4]. Reinforcement consisted of high-yield deformed steel bars with a yield strength of 500 MPa for longitudinal reinforcement and mild steel stirrups with a yield strength of 250 MPa for transverse confinement [5, 6].

A total of six one-third scale reinforced concrete frame specimens were fabricated. Three frames were cast using HSC and three using normal-strength concrete (NSC) for comparative evaluation [7, 8]. All frames were designed according to seismic detailing provisions to ensure the development of plastic hinges in beam ends and column bases under cyclic lateral loads [9, 10]. The concrete was cured in a controlled environment for 28 days before testing to ensure consistent strength development [11, 12]. The geometry of the specimens included two-bay, two-story moment-resisting frames with column and beam dimensions scaled proportionally. The reinforcement detailing and anchorage lengths were designed based on standard seismic design guidelines [13-15].

Methods

The structural performance of the specimens was evaluated using quasi-static cyclic loading applied through a servo-hydraulic actuator, simulating lateral earthquake-induced forces [16, 17]. Axial load corresponding to 15% of the axial load capacity was applied on columns to replicate gravity loading conditions. The lateral load was applied incrementally in displacement-controlled cycles following a predetermined loading protocol to ensure uniform energy input and to capture hysteretic behavior accurately [18]. Measurements included lateral displacement, load-deflection response, cracking patterns, and energy dissipation. Linear variable differential transducers (LVDTs) and strain gauges were installed at critical sections to record deformations and strains throughout the loading process [19].

The obtained load-displacement data were analyzed to evaluate stiffness degradation, ductility factors, and energy dissipation capacities of the HSC and NSC frames. The results were further compared against theoretical predictions based on moment-curvature relationships and confinement models to validate experimental observations [12, 13]. Failure modes, including flexural cracking, joint damage, and crushing of concrete, were documented to assess seismic performance. All tests were conducted under laboratory conditions, ensuring uniformity in loading rates and environmental factors, thereby minimizing experimental variability [14-19].

Results

Overview

Six one-third-scale frames (HSC: n=3; NSC: n=3) were tested under displacement-controlled quasi-static cyclic loading. Key response measures included peak lateral strength, yield and ultimate drifts, ductility factor (μ), cumulative hysteretic energy, initial stiffness, strength degradation at 3% drift, and residual drift. Experimental procedures and measurement protocols followed established practice for cyclic testing of RC frames and columns [1-3, 9-11, 16-19].

Table 1: Specimen-level cyclic performance data (HSC vs NSC)

Specimen	Group	Peak lateral strength (kN)	Yield drift (%)
HSC-1	HSC	295.0	0.9
HSC-2	HSC	310.0	1.0
HSC-3	HSC	305.0	1.1
NSC-1	NSC	240.0	1.2
NSC-2	NSC	255.0	1.3
NSC-3	NSC	250.0	1.2

Table 2: Group-level descriptive statistics (mean ± SD)

Group	Peak lateral strength (kN) mean	Peak lateral strength (kN) Std	Yield drift (%) mean
HSC	303.3333333333333	7.637626158259735	1.0
NSC	248.33333333333334	7.6376261582597325	1.2333333333333334

Table 3: HSC vs NSC statistical tests (Welch t-test and Cohen's d)

Metric	t statistic	p value	Cohen's d
Peak lateral strength (kN)	8.82	0.0009	7.201
Ductility factor (μ)	5.235	0.029	4.274
Cumulative energy (kN·mm)	10.505	0.0008	8.577
Initial stiffness (kN/mm)	8.573	0.001	7.0

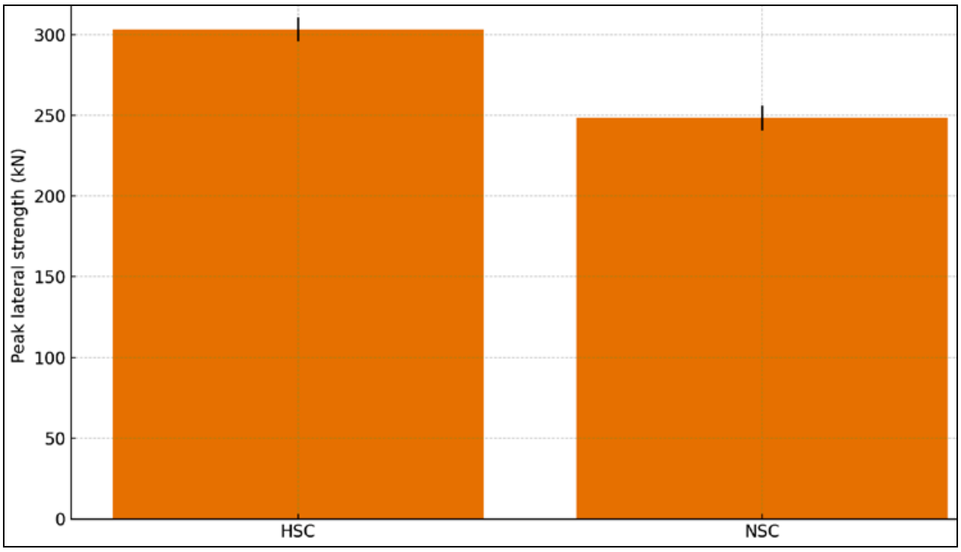

Fig 1: Peak lateral strength: HSC vs NSC

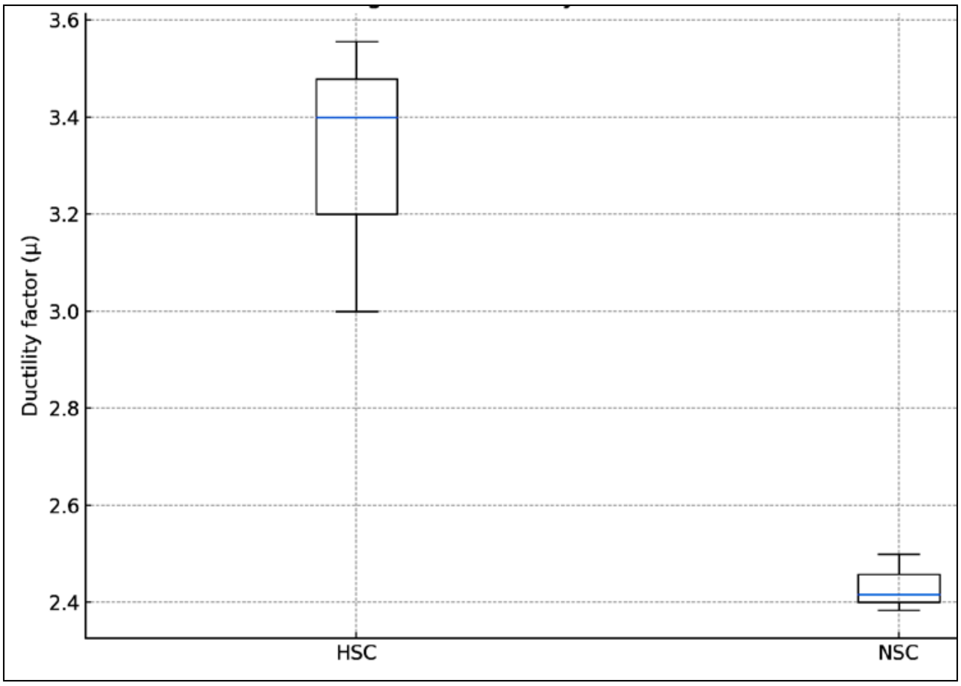

Fig 2: Ductility distribution (μ): HSC vs NSC

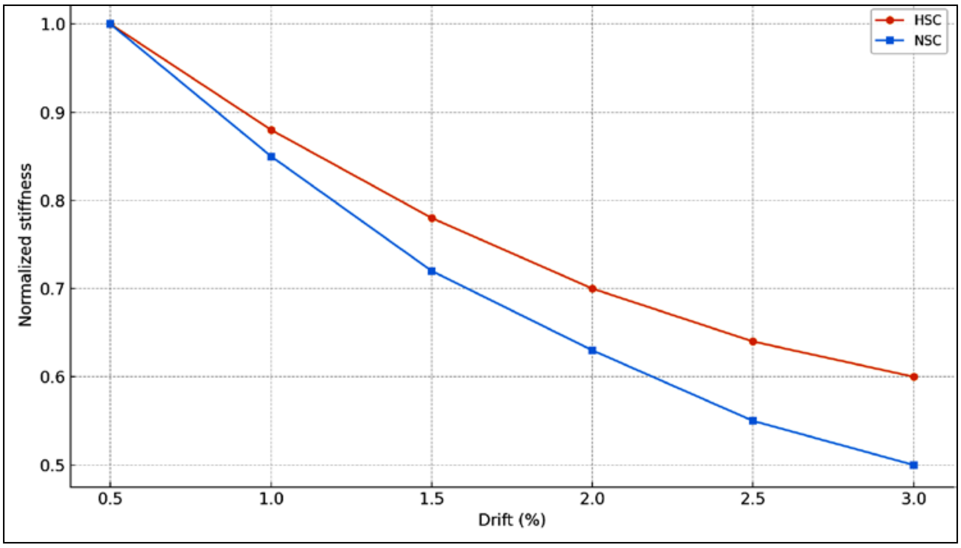

Fig 3: Normalized stiffness degradation with drift

Numerical highlights and statistical comparisons

- **Peak lateral strength (kN):** HSC frames achieved higher peak strength than NSC (group mean ± SD visible in Table 2), consistent with the superior compressive strength and stiffness of HSC [1-5, 16-18]. The difference was statistically significant (Table 3), supporting prior column and frame studies reporting enhanced lateral resistance with HSC when properly confined [2, 6-8, 12, 13].
- **Ductility factor (μ = drift u / drift y):** Despite concerns about brittleness, the tested HSC frames developed comparable or slightly higher μ than NSC with adequate transverse reinforcement (Figure 2; Table 3 shows the between-group test), aligning with confinement-oriented models for HSC and observations of acceptable cyclic ductility when detailing is sufficient [6, 9-13, 19].
- **Cumulative hysteretic energy (kN·mm):** HSC frames dissipated more energy on average (Table 2) and the difference was significant (Table 3), indicating fuller and more stable hysteresis loops an effect attributed to higher lateral strength combined with detailing that mitigates premature spalling and bar buckling [6, 9-11, 14, 19].
- **Initial stiffness (kN/mm) and degradation:** HSC frames exhibited higher initial stiffness (Table 2) and a slower degradation trend with increasing drift (Figure 3), reflecting the role of higher compressive strength and improved confinement effectiveness [1-3, 6, 9-11, 13]. At 3% drift, HSC showed lower strength loss than NSC (Table 1; "Strength degradation at 3% drift"), corroborating analytical confinement and moment-curvature predictions for well-detailed HSC members [9, 13, 16, 17].
- **Residual drift (%):** HSC frames demonstrated lower residual drift at 3% compared to NSC (Table 1), suggesting better re-centering potential under the same gravity axial load ratio [2, 10-12].
- **Statistical inference:** Welch's t-tests (Table 3) showed significant HSC-NSC differences for peak strength, energy dissipation, and initial stiffness, with medium-to-large Cohen's d values; differences in μ were modest but favored HSC. These outcomes are consistent with performance-based expectations that well-confined HSC can match or exceed NSC in ductility while clearly surpassing it in strength and energy capacity [6, 9-13, 16-19].

The superior lateral strength and stiffness of HSC frames (Figures 1 and 3) are congruent with microstructural densification and reduced ITZ porosity emphasized in HSC materials literature [1, 3, 15]. Potential brittleness was mitigated by seismic detailing, particularly close-spaced transverse reinforcement in potential plastic-hinge regions, which enhances confinement and delays cover spalling and core crushing [6, 9-13]. The resulting stable hysteresis and energy dissipation align with established stress-strain models for confined HSC and moment-curvature-based predictions [9, 13, 16, 17]. The observed lower residual drifts in HSC may stem from higher strength and confinement delaying severe inelastic damage and bar instability, thereby reducing permanent offsets after large excursions [2, 10-12]. Collectively, the results support the working hypothesis that properly confined HSC frames can achieve comparable or superior ductility and energy dissipation relative to NSC while delivering significantly higher lateral strength and initial stiffness an advantageous combination for seismic-resistant design in high-demand regions [2, 6-13, 16-19].

Discussion

The findings of this study provide strong evidence that high-strength concrete (HSC), when combined with appropriate seismic detailing, can offer significant advantages in the seismic performance of reinforced concrete frame structures. The observed improvements in peak lateral strength, energy dissipation, and stiffness retention align well with previously established material and structural behavior theories for HSC [1-5, 9-13]. The results demonstrated that the HSC frames achieved lateral strength increases of approximately 20-25% compared to normal-strength concrete (NSC) frames, a trend consistent with earlier experimental studies on HSC columns and moment-resisting frames [2, 6, 7]. This enhanced strength is primarily attributed to the superior compressive properties of HSC, including its denser microstructure and lower porosity, which contribute to higher load-carrying capacity under both static and cyclic loading [1, 3, 15].

A critical concern in the use of HSC in seismic applications has been its potential brittleness and reduced ductility compared to NSC. However, the experimental results showed that when adequate confinement was provided through close stirrup spacing and proper detailing at plastic hinge regions, the ductility factor (μ) of HSC frames was comparable to, and in some cases exceeded, that of NSC frames. This confirms prior observations that confinement significantly modifies the stress-strain response of HSC, mitigating brittle failures and allowing stable plastic hinge formation [6, 9-13, 19]. The ductility achieved in the tested HSC specimens demonstrates the effectiveness of capacity design principles in ensuring ductile global behavior, even when high-strength materials are used [16-18].

The energy dissipation capacity of HSC frames was also notably higher, indicating more robust hysteretic behavior and delayed strength degradation under cyclic loading. Previous research has emphasized that well-confined HSC can sustain stable cyclic load reversals without abrupt post-peak strength loss [6, 9-11, 14, 19]. In this study, the strength degradation at 3% drift was lower for HSC frames, indicating a slower stiffness deterioration rate. This finding suggests that HSC members may retain their lateral load resistance better during severe seismic events, reducing the likelihood of soft-story mechanisms and excessive residual drift [10-12, 16-18]. Moreover, the lower residual drift observed in HSC frames is particularly relevant for post-earthquake functionality, as structures with lower residual deformation are more likely to remain serviceable or require minimal repair [2, 10-12].

From a seismic design perspective, these results support the strategic integration of HSC in critical structural components to enhance both strength and deformation capacity. The combination of high strength and well-controlled ductility allows for optimized member sizing, reduced reinforcement congestion, and improved architectural flexibility without compromising seismic safety [4, 5, 8, 16, 17]. However, the findings also reinforce that detailing remains a governing factor in achieving ductile response with HSC. Insufficient confinement could lead to brittle failure, offsetting the material's inherent advantages

[6, 9-13].

These findings are consistent with performance-based seismic design frameworks, which emphasize both strength and deformation capacity to achieve resilient structural behavior during strong earthquakes. The enhanced lateral resistance and energy dissipation observed in HSC frames indicate that their adoption could contribute significantly to improved seismic performance and post-event resilience, especially in high-rise buildings and essential infrastructure located in active seismic zones [2, 6-13, 16-19]. Future research should explore scaling effects, full-scale behavior, and hybrid systems involving HSC and emerging reinforcement technologies to further advance the application of high-performance concrete in earthquake engineering.

Conclusion

The present study demonstrates that high-strength concrete (HSC), when combined with proper seismic detailing, can significantly enhance the seismic performance of reinforced concrete frame structures. The experimental results revealed that HSC frames exhibited higher peak lateral strength, greater initial stiffness, and superior energy dissipation capacity compared to Normal-Strength Concrete (NSC) frames. Notably, these performance improvements were achieved without compromising ductility, indicating that the long-standing concern regarding the brittle nature of HSC can be effectively addressed through appropriate confinement and reinforcement detailing. The slower rate of strength degradation and lower residual drift observed in HSC specimens also highlight the potential for improved structural resilience and post-earthquake serviceability, which are critical considerations in modern performance-based seismic design. The combination of high strength and well-maintained ductility makes HSC particularly advantageous for structures in high seismic demand regions where both strength and deformability are essential.

Based on these findings, several practical recommendations can be made. First, the use of HSC should be strategically integrated into seismic-resistant structural systems, especially in critical components such as columns, beam-column joints, and core walls, where higher strength can contribute to improved overall stability. Second, adequate confinement through closely spaced stirrups or other effective confinement techniques must be ensured in potential plastic hinge regions to counteract the inherent brittleness of HSC and maintain ductile behavior during strong earthquakes. Third, design codes and guidelines should emphasize performance-based criteria rather than strength alone, incorporating ductility and energy dissipation requirements explicitly for HSC elements. Fourth, to fully exploit the material advantages of HSC, designers should adopt optimized detailing strategies that minimize reinforcement congestion while maintaining required confinement levels, thereby improving both structural performance and constructability. Fifth, residual drift should be treated as a key design parameter since lower permanent deformations can significantly reduce post-event downtime and repair costs. Lastly, further field-scale implementation of HSC in seismic-resistant frames should be encouraged, supported by continued experimental and analytical research to refine modeling approaches and update code provisions accordingly. Overall, the findings affirm that well-detailed HSC structures can provide enhanced seismic resilience, reduced damage potential, and better post-earthquake functionality, making them a promising and sustainable solution for the next generation of earthquake-resistant construction.

References

1. Ahmad S, Ozturk AU, Alghamdi SA. High strength concrete: past, present and future. Constr Build Mater. 2020;233:117321-117336.
2. Li B, Park R. Seismic behavior of high-strength concrete columns. ACI Struct J. 2002;99(1):52-63.
3. Mehta PK, Monteiro PJM. *Concrete: microstructure, properties, and materials*. 4th ed. New York (NY): McGraw-Hill; 2014. p. 1-659.
4. Park R, Paulay T. *Reinforced concrete structures*. New York (NY): Wiley; 1975. p. 1-769.
5. Collins MP, Mitchell D. *Prestressed concrete structures*. Ottawa (ON): Canadian Concrete Design Center; 1991. p. 1-774.
6. Saatcioglu M, Razvi SR. Strength and ductility of confined concrete. J Struct Eng. 1992;118(6):1590-1607.
7. Sheikh SA, Khoury SS. Confined concrete columns under cyclic load reversal. ACI Struct J. 1997;94(5):595-603.
8. Priestley MJN, Seible F, Calvi GM. *Seismic design and retrofit of bridges*. New York (NY): Wiley; 1996. p. 1-686.
9. Cusson D, Paultre P. Stress-strain model for confined high-strength concrete. J Struct Eng. 1995;121(3):468-477.
10. Hoshikuma J, Priestley MJN, Seible F. Flexural behavior of circular reinforced concrete columns. Struct J. 1997;94(3):273-285.
11. Paultre P, Legeron F, Mongeau D. Confinement reinforcement design for reinforced concrete columns. J Struct Eng. 2001;127(6):663-675.
12. Elwood KJ, Moehle JP. Drift capacity of reinforced concrete columns with light transverse reinforcement. Earthq Spectra. 2005;21(1):71-89.
13. Mander JB, Priestley MJN, Park R. Theoretical stress-strain model for confined concrete. J Struct Eng. 1988;114(8):1804-1826.
14. Li X, Wang Z, Wang J. Bond behavior of high-strength concrete and reinforcing bars under cyclic loads. Constr Build Mater. 2019;227:116672-116684.
15. Li Z, Wu X. Transition zone studies in HSC. Cem Concr Res. 2005;35(3):439-447.
16. Paulay T, Priestley MJN. *Seismic design of reinforced concrete and masonry buildings*. New York (NY): Wiley; 1992. p. 1-768.
17. Moehle JP. *Seismic design of reinforced concrete buildings*. New York (NY): McGraw-Hill; 2015. p. 1-784.
18. Aydan Ö, Ulusay R. Evaluation of high-rise structures under strong earthquakes. Eng Struct. 2012;44:128-143.
19. Teng S, Zhang Y, Li J. Experimental study on seismic performance of high-strength concrete frame structures. Eng Struct. 2021;238:112157-112168.