

Ultra High Performance Concrete's Mechanical Properties at Elevated Temperature: A review*

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Abstract— Ultra High Performance Concrete (UHPC) is known for its exceptional mechanical strength and durability, yet its effectiveness is notably compromised when subjected to high temperatures. This study investigates the temperature-dependent mechanical properties of UHPC, with emphasis on residual compressive and tensile strengths. The influence of critical parameters such as steel fiber content, polypropylene fiber dosage, water-to-binder ratio, and supplementary cementitious materials is systematically analyzed. Experimental findings from existing literature indicate that increasing temperature leads to strength degradation due to microcracking, matrix densification loss, and fiber–matrix debonding. The inclusion of polypropylene fibers is found to mitigate explosive spalling by enhancing vapor pressure release. Furthermore, artificial neural network models are explored to predict residual mechanical properties of UHPC under thermal exposure. The outcomes contribute to a better understanding of UHPC behavior in fire-prone structural applications.

Keywords: Ultra-High Performance Concrete; Elevated Temperature; Mechanical Properties; Residual Strength; Steel Fibers; Polypropylene Fibers; Spalling; Thermal Damage.

I. INTRODUCTION

Ultra-High-Performance Concrete (UHPC) is a cutting-edge cement-based material known for its remarkable mechanical strength, longevity, and ability to withstand harsh conditions. Compared with conventional and high-strength concrete (HSC), UHPC typically achieves compressive strengths exceeding 120 MPa and tensile strengths above 7 MPa, owing to its dense microstructure and optimized particle packing [1]. UHPC mixtures consist of fine constituents such as Portland cement, silica fume, quartz powder, fine sand, and supplementary cementitious materials, combined with a low water-to-binder ratio (0.20– 0.25) and high-range water-reducing admixtures to ensure workability. The inclusion of steel or synthetic fibers significantly enhances ductility, flexural capacity, energy absorption, and crack resistance [3–5].

The superior performance of UHPC results from the synergistic interaction of its mechanical, physical, and thermal properties. Mechanically, UHPC exhibits high strength and stiffness, enabling the construction of slender and durable structural elements such as bridge decks and precast components [6–8]. Fiber reinforcement improves post-cracking behavior, with strain-hardening commonly observed in mixtures containing more than 1% micro steel fibers by volume [9–11]. Mechanical performance is strongly influenced by fiber type, geometry, volume fraction, and distribution through fiber–matrix bonding and crack-bridging mechanisms

[12–15]. UHPC also demonstrates extremely low permeability and porosity due to its compact microstructure, which restricts the ingress of harmful agents and enhances resistance to freeze–thaw cycles, chloride penetration, and carbonation [12].

However, this dense matrix presents challenges under elevated temperatures. UHPC generally exhibits higher thermal conductivity than conventional concrete, but exposure to temperatures between 300°C and 500°C leads to dehydration of calcium hydroxide and calcium silicate hydrate phases, resulting in strength degradation and internal stress development [15]. The risk of explosive spalling increases due to vapor pressure buildup, particularly in fiber-free mixtures. Polypropylene fibers mitigate spalling by melting and creating vapor escape channels. Fire exposure poses a significant threat to the safety and structural performance of reinforced concrete members [5].

Standardized fire resistance testing methods have therefore been developed, with ISO 834 widely adopted as the international reference time-temperature curve for evaluating fire performance [16]. In addition, several regional standards are commonly used in fire resistance studies of reinforced concrete elements, as summarized in Table 1. Ultra-High-Performance Fiber-Reinforced Concrete (UHPRFC), an advanced form of UHPC, further enhances thermal stability and fire resistance through the use of hybrid fiber systems. Commonly employed fibers include steel, polypropylene,

polyethylene, polyvinyl alcohol, nylon, carbon, and basalt fibers.

Regional adaptations like IS 3809 (India) and GB/T 9978 (China) align closely with ISO 834 while incorporating local material specifications and construction norms. European EN 1363 introduces flexibility for parametric fires or cooling regime evaluation, critical for modern performance-based design. BS 476 emphasizes surface fire spread metrics alongside endurance. ISO 834 establishes the global

benchmark using bare K-type thermocouples and a fixed time-temperature curve without post-exposure testing, making it ideal for universal research comparability. ASTM E119 closely mirrors this curve but employs sheathed thermocouples for radiation protection and uniquely incorporates a hose stream test to simulate firefighter water impact on heated assemblies-critical for assessing UHPC spalling vulnerability[13]. EN 1363 offers the greatest

Table 1: Summary of major international standards for evaluating fire resistance of construction elements

Standard designation	Region/Country	Organization	Primary focus and test methodology	Key exposure curve	Common applications
ISO 834	International	International Organization for Standardization	Standard time-temperature curve simulating realistic building fire growth; evaluates load-bearing capacity, integrity, and thermal insulation	ISO 834 fire curve	Benchmark for global fire testing; walls, floors, beams, columns
ASTM E119	United States	ASTM	Furnace testing + hose stream test; assesses mechanical endurance and thermal insulation under fire	ASTM E119 (similar to ISO 834)	Building assemblies, structural elements, fire endurance ratings
BS 476	United Kingdom	BSI	Comprehensive suite: fire resistance, ignitability, flame spread, smoke generation	BS 476 Part 20 (ISO 834 equivalent)	Loadbearing/non-loadbearing elements, surface treatments
IS 3809	India	BIS	Fire endurance of structural elements; adapted for local construction practices	IS 3809 (ISO 834 based)	Walls, floors, beams; Indian building codes
JIS A 1304	Japan	Japanese Industrial Standards	Structural component fire resistance; load capacity, insulation, integrity	JIS A 1304 (ISO 834 aligned)	Slabs, beams, walls; seismic regions
AS 1530	Australia	Standards Australia	Fire resistance procedures; structural failure, integrity, insulation criteria	AS 1530 Part 4 (ISO 834)	Construction elements; Australian building codes
EN 1363	European Union	European Committee for Standardization	General/alternative procedures; variable heating rates, cooling phases	EN 1363-1 (ISO 834 standard)	Structural/non-structural; EU harmonized standards
GB/T 9978	China	Standardization Administration of China	National fire resistance testing; structural/non-structural elements	GB/T 9978 (ISO 834 model)	Building materials, structural systems; Chinese codes

II. SPALLING OF CONCRTE

Spalling in concrete at high temperatures significantly reduces its mechanical properties and can even lead to the collapse of the structure. The primary mechanisms behind spalling are associated with two key factors: vapor pressure in pores and

thermal stresses shown in Fig.1. Hardened concrete contains varying amounts of water within its pores, influenced by factors such as the water-to-binder ratio (w/b), concrete age, and environmental conditions. When the surface of concrete is exposed to high temperatures, some water vaporizes and escapes into the atmosphere, while some moves inward[12]. Due to the thermal gradient, the inner parts of the concrete

remain cooler, causing the inward- moving vapor to condense, forming a saturated layer.

This layer blocks further vapor movement inward and forces the vapor outward toward the dry surface. If the pressure within the pores surpasses the concrete's tensile strength, spalling will occur. In high-strength concrete, the denser pore structure reduces permeability, making it harder for vapor to escape[6].

Thermal gradients between the heated surface and the cooler inner layers generate compressive stress parallel to the surface and tensile stress perpendicular to it. Rapid temperature increases, referred to as "thermal shock," exacerbate these stresses. When compressive stress surpasses tensile stress, spalling occurs [5].

Additionally, cracking at high temperatures is influenced by factors such as the decomposition of hydration products, cement matrix shrinkage, aggregate expansion, and the differing thermal responses of the cement matrix and aggregates. These stresses damage the interfacial transition zone (ITZ) and concrete's meso-structure, leading to various types of spalling, including aggregate spalling, surface spalling, corner spalling, and explosive spalling.

The three spalling mechanism illustrated represent progressive UHPC degradation pathway a) Thermal stress mechanism: initiates when surface heating creates 200-400°C gradients, causing restrained expansion that generates 15–25 MPa hoop compression; combined with 20–40% design load, this exceeds tensile capacity (3–5 MPa), forming radial cracks and surface fragmentation, steel fibers reduce effective stress by 30–50% through bridging (Kodur & Banerji, 2021; Zhu et al., 2021). b) Vapor pressure mechanism dominates 300– 500°C as free/bound water vaporizes in sealed nanopores (<0.1 μm), accumulating 3–8 MPa (critical threshold 2.8 MPa); low permeability traps steam, rupturing capillaries and expelling 10–50 mm layers-PP fibers (0.2 vol%) melt at 165°C, forming 100–500 μm relief channels reducing pressure 70–90% (Liang et al., 2018; Han et al., 2025).c)

Combine thermal stress and pore pressure mechanism triggers explosive failure >500°C when CH decomposition (430–600°C) and HRWR pyrolysis generate CO/CO₂ in pre-cracked matrix, surging P_v >10 MPa; quartz α→β transition (573°C) and SF expansion (0.5%) exacerbate shock-hybrid SF+PP systems suppress via mechanical restraint + residual channels, limiting damage depth to <20 mm

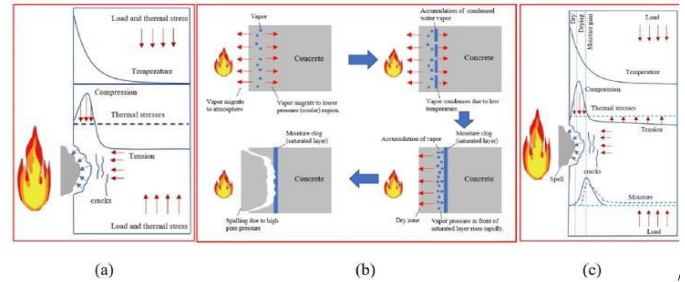


Figure 1:Spalling due to a) Thermal stress b) pore pressure c) combined thermal and pore pressure

Fiber Selection For UHPC

Steel fibers (SF) remain the most prevalent reinforcement in UHPC due to their exceptional tensile strength (>2500 MPa typical) and high density (7.75–7.89 g/cm³), which provide robust crack-bridging and maintain structural capacity even at elevated temperatures up to 600°C[17]. Polypropylene (PP) fibers, conversely, offer unique thermal benefits through their low density which generates vapor escape pathways and effectively suppresses explosive spalling[18]. Polyvinyl alcohol (PVA) fibers contribute moderate tensile reinforcement (900–1200 MPa) and density 1.3 g/cm³, improving overall ductility and post-peak performance.

Steel fibers (SF), with their high density (7.75– 7.90 g/cm³), exceptional tensile strength (900–3070 MPa), and elastic modulus (190–210 GPa), serve as the primary load bearing reinforcement across 6–50 mm lengths and 0.12–1.05 mm diameters.

Polypropylene (PP) melting at 165°C creates essential vapor escape channels, making 0.1–0.3 vol% optimal for hybrid systems despite limited tensile contribution. Polyvinyl alcohol (PVA) provides balanced ductility (900–1200 MPa tensile, 20–30 GPa modulus) through 6–12 mm straight fibers at 1.25–1.30 g/cm³ density, effectively controlling microcracking while maintaining matrix cohesion up to 400°C. Nylon/PET/PA fibers (700– 900 MPa, 6–9 GPa modulus) serve supplementary roles in 6-12 mm circular forms, enhancing toughness without dominating mix economics. Carbon fibers (CF) provide niche high-stiffness reinforcement (~380 GPa modulus, ~3000 MPa tensile) via hooked 35 mm lengths, though limited matrix bonding reduces practicality[19]. Hybrid optimization typically 1–2% SF vol + 0.15-0.3% PP delivers synergistic performance: steel ensures mechanical capacity while polymers prevent explosive failure. Selection prioritizes project requirements (fire rating, ductility

demands) against cost, workability, and long-term durability[20]. Steel fibers at 1.5 vol% (13 mm length, 0.2 mm diameter) achieve 52 MPa residual compressive strength at 800°C, representing 29% ambient retention with no spalling, though crack widths increase 15% compared to hybrids (Abadel et al., 2023). Polypropylene fibers alone at 1.2 vol% (12–19 mm lengths) completely eliminate spalling at 1000°C while retaining 58 MPa (>50 MPa target), with [21]

longer 19 mm variants outperforming shorter fibers (Ma et al., 2024). PVA at 1 vol% (12 mm) preserves 32% flexural capacity at 600°C but exhibits 45% spalling risk without steel pairing (Xiong et al., 2015; validated 2024). Synergistic flame-retardant PP (2 vol%) with organic-metallic fillers delays degradation 65% beyond conventional PP (Zhang et al., 2024)

Table 1: Fiber properties at Elevated Temperature

Fiber type	Fibre geometry / form	Density (g/cm ³)	Length (mm)	Diameter (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Primary role at elevated temperature
Steel fiber (SF)	Straight / hooked / micro / flat	7.75–7.90	6–50	0.12–1.05	190–210	900–3070	Strength retention, crack bridging, post-fire integrity
Polypropylene (PP)	Monofilament / cylindrical	0.90–0.92	6–24	0.02–0.06	3–5	400–750	Spalling mitigation via melting and vapor release-
Polyvinyl alcohol (PVA)	Straight	1.25–1.30	6–12	0.015–0.66	20–30	900–1200	Ductility enhancement and micro-crack control
Polyethylene (PE / UHMWPE)	Straight	0.95–0.97	12–18	0.026–0.032	100–120	2900–3200	High tensile reinforcement and crack resistance
Basalt fiber (BF)	Straight / twisted	2.6–2.8	9–12	0.013–0.42	44–90	1300–2200	Thermal stability and strength retention
Nylon / PET / PA	Circular / straight	1.10–1.40	6–12	0.02–0.23	6–9	700–900	Secondary reinforcement and toughness
Carbon fiber (CF)	Hooked / straight	~1.80	~35	~0.018	~380	~3000	High-temperature tensile reinforcement
Hybrid fibers	SF + PP / SF + PVA / SF + PE	-	-	-	-	-	Combined mechanical strength and spalling resistance

Thermal Impact On UHpc’s Mechanical Behaviour

Compressive strength

Bolina et al. (2023) observed UHPC maintaining stable UHPC demonstrates superior ambient mechanical characteristics, yet its response to elevated temperatures is highly dependent on its compact microstructure[23]. This section examines temperature-induced changes in key properties. After 300°C exposure, UHPC compressive strength shows consistent reduction, retaining approximately 0.35 of ambient capacity (63 MPa at 800°C)-still outperforming NSC's 0.15 retention (4.5 MPa)[24][25]. This superior behavior stems from UHPC's tightly packed cement matrix and silica fume's high pozzolanic activity, which significantly lowers porosity. Notably, Fig.2 illustrates strength surpassing the original 180 MPa value, reaching 198

MPa beyond 150°C, credited to the continuous pozzolanic reaction of silica fume, which generates additional C-S-H gel, thereby improving durability.strength up to 300°C (170 MPa), dropping to 110 MPa at 600°C-compared to NSC's mere 13.5 MPa at the same temperature[26]. At 800°C, UHPC achieves 68 MPa, substantially exceeding NSC's ambient capacity. Steel fiber incorporation effectively postpones crack growth and limits spalling damage. Fiber expansion counteracts microcracking under heat, preserving greater residual capacity. Huang et al. (2023) reported UHPC sustaining 132 MPa up to 600°C, with 91 MPa retention at 800°C-far superior to NSC's baseline. Quartz fine aggregates bolster resistance to thermal gradients, while elevated silica content supports mid-temperature strength gains, though quartz phase changes beyond 600°C impair performance. Banerji and Kodur et al. demonstrated hybrid fiber UHPC retaining 50 MPa at 500°C, with controlled decline at 800°C. Steel fibers ensure tensile reinforcement,while polypropylene fibers

generate vapor relief networks, collectively suppressing spalling and crack development[27].

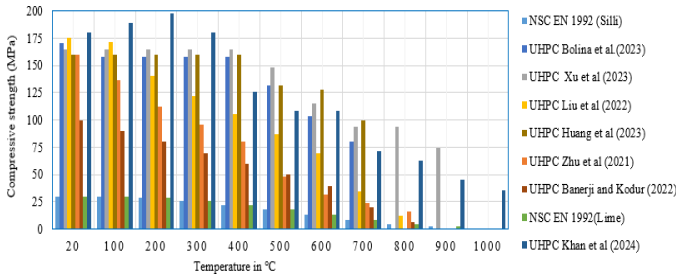


Figure 2: Variation of compressive strength with temperature

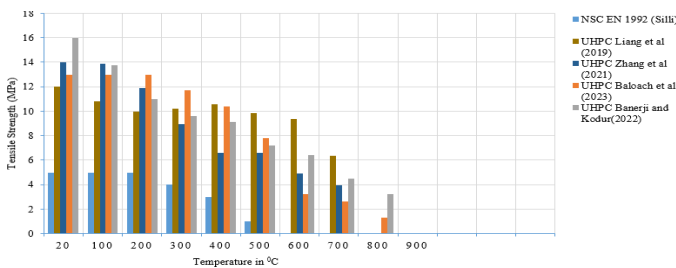


Figure 3: Variation of Tensile strength with temperature

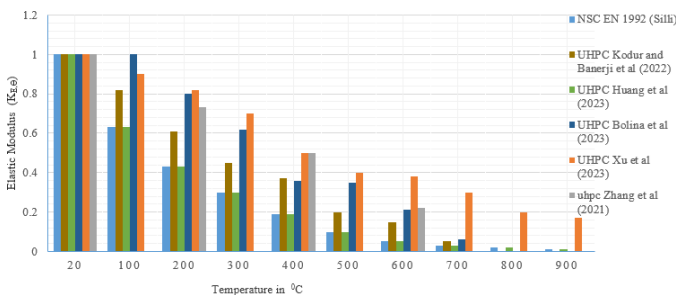


Figure 4: Variation of Elastic modulus with Elevated Temperature

III. CONCLUSION

- UHPC demonstrates remarkable mechanical superiority over conventional concretes under fire exposure, retaining 35–40% compressive strength at 800°C compared to NSC's 15%, primarily due to its dense microstructure and optimized fiber reinforcement.
- Hybrid SF+PP systems (1.4–1.8 vol% total, 5:1 ratio) emerge as optimal, achieving >50% strength retention at 1000°C while completely eliminating spalling through synergistic crack bridging and vapor relief. Steel fibers maintain structural integrity up to 600°C, while PP melting at 165°C prevents pressure buildup; PVA/BF supplements enhance ductility and sustainability

- The synthesis of compressive, tensile, and stiffness data indicates that degradation of elastic modulus is more severe than that of strength, reflecting progressive microcracking, decomposition of CH and C–S–H, and deterioration of the fiber–matrix interface as temperature approaches 750–900°C.
- Nevertheless, UHPC generally maintains higher relative stiffness than NSC over the same temperature range, suggesting continued advantages for stiffness-critical members such as slender columns and precast elements.
- Properly engineered UHPC, incorporating optimized hybrid fibers and suitable supplementary cementitious materials, can deliver reliable mechanical performance and improved fire resistance, making it a strong candidate for critical infrastructure and high-risk structures.

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