

Analysis Of Behavior of Ultra-High-Performance Concrete (UHPC) Under Compressive and Flexural Loading

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ABSTRACT

Ultra-high performance concrete (UHPC) combines a very dense cementitious matrix with, in most formulations, discontinuous steel fibers, giving compressive strengths above about 150 MPa and a tensile and flexural response that conventional and high-performance concretes cannot match. This article is a narrative critical review of published evidence on the behavior of UHPC and fiber-reinforced UHPC (UHPFRC) under compressive and flexural loading. It summarizes materials, mix-design principles and microstructure; the test methods and standards used to measure compressive strength, modulus, flexural strength and toughness; and the evidence on stress-strain response, flexural and post-cracking behavior, fiber content, geometry and orientation, curing, water-to-binder ratio, specimen size, sustainability and structural applications. Evidence is compared in tables that record material characteristics, fibers, curing, test method, findings and limitations of each study. The synthesis shows broad agreement that compressive strength is governed mainly by matrix packing and curing, and that flexural and post-cracking performance depends on fiber content, geometry, orientation and bond. It also shows disagreements, for example on whether fibers raise compressive strength and on which fiber length is most effective in flexure, and discusses methodological reasons for them. The review was not conducted as a systematic review: sources were located by targeted searches, and verification was mostly limited to abstracts and publisher records. The paper therefore reports no original experimental data, does not claim completeness, and identifies research gaps in test standardization, orientation control, size and rate effects, recent-literature coverage and life-cycle assessment.

KEYWORDS

Ultra-high performance concrete; UHPFRC; compressive behavior; flexural behavior; steel fibers; fiber orientation; curing; critical review

1. INTRODUCTION

Concrete is the most widely used construction material, yet conventional concrete is limited by low tensile strength, brittle failure and, in aggressive environments, limited durability. Successive material developments, including high-strength concrete and high-performance concrete (HPC), have improved strength and durability but have generally increased brittleness. UHPC was developed to address this trade-off by combining very high compressive strength with significant tensile capacity and energy

absorption.

The modern concept of UHPC is commonly traced to reactive powder concrete (RPC), in which coarse aggregate is removed, the particle-size distribution is optimized, the water-to-binder ratio is made very low, and fibers and thermal treatment are used to obtain exceptional properties (Richard & Cheyrezy, 1995). Subsequent European and North American work, including guidelines, state-of-the-art reports and bridge applications, consolidated UHPC as a distinct class of material (Schmidt & Fehling, 2005; Fehling et al., 2014; Russell & Graybeal, 2013; ACI Committee 239, 2018). Definitions summarized in a recent review require a compressive strength above about 150 MPa and a sustained post-cracking tensile strength above about 5 MPa (Ullah et al., 2022). In this paper, UHPFRC denotes the fiber-reinforced form of UHPC, and UHPC is used for the material class in general.

Compressive and flexural loading are the two most informative and most widely reported actions for characterizing UHPC. Compression reflects the quality of the matrix and its packing, whereas flexure integrates matrix cracking, fiber bridging and post-cracking resistance into a single test that is directly relevant to beams, girders and thin slabs. Reported values differ between studies because of differences in mixture, specimen size, curing, fiber orientation and test procedure, which complicates direct comparison and design use. A critical comparison of the evidence on these two actions is therefore useful.

Review questions. This review addresses the following questions:

1. What levels and mechanisms of compressive and flexural performance are reported for UHPC and UHPFRC?
2. How do fiber content, geometry and orientation, curing, water-to-binder ratio and specimen size affect these properties, and where do studies agree or disagree?
3. What methodological limitations restrict comparison between studies?
4. What research gaps follow from the evidence?

Scope and limitations. This is a narrative critical review. It does not include original experiments, and it was not conducted as a systematic review (Section 2). Numerical values are given only where traceable to a cited source, and statements that are the author's own synthesis are labelled as such.

2. REVIEW METHODOLOGY

2.1 Type of review

The paper is a narrative critical review with structured tabulation of evidence. It is not a systematic review or meta-analysis: no protocol was registered, no formal reporting framework such as PRISMA was followed, and no numbers of records identified, screened or excluded are reported because these were not systematically recorded. [AUTHOR INPUT REQUIRED: confirm with the supervisor that a narrative critical review is acceptable for the target journal.]

2.2 Sources and search

Literature was located during manuscript preparation (to October 2026) using targeted queries in a general web search engine, which returned publisher pages, open-access repositories (including PubMed Central and MDPI), institutional repositories, and the websites of ASTM International and the U.S.

Federal Highway Administration (FHWA). Dedicated bibliographic databases (for example Scopus, Web of Science or ScienceDirect) were not searched. Queries combined the terms ultra-high performance concrete or UHPFRC with: compressive strength; stress-strain; flexural strength or toughness; steel fiber content; fiber orientation or distribution; curing or steam curing; life-cycle assessment; and ASTM C1856. Foundational papers already known to the author were looked up by title. Publication years were not restricted, with priority given to 2019-2026 work and to the foundational studies that define the field.

2.3 Eligibility

Included: peer-reviewed articles, official technical reports and applicable standards on UHPC or UHPFRC that report compressive, flexural, tensile or fiber-related behavior, specimen testing, curing, sustainability or structural application, and whose bibliographic details could be confirmed. Excluded: sources whose authors, journal or year could not be confirmed (these are listed in the accompanying editorial report rather than cited); patents; theses and conference abstracts without citable details; and studies on materials outside the UHPC class. Language was restricted to English. No formal quality scoring was applied.

2.4 Screening and verification

Candidate sources were screened by title and abstract. For each cited source, bibliographic details and the findings used in the tables were checked against the abstract or record page where it was accessible. Full texts were not read for most sources, so the tables report abstract-level findings, and details that are not available at that level are marked [AUTHOR INPUT REQUIRED] or “not stated”. Sources are labelled in the reference list by verification level (see Section 12 note).

2.5 Synthesis approach

Evidence was organized by loading type and by influencing factor. Each source was summarized in the evidence tables (Tables 3 and 4) with its material, fiber, curing, test method, findings and limitations. Agreements and disagreements were identified by comparing findings for the same factor, and possible reasons for differences were proposed. These reasons are the author’s interpretation and are labelled as such.

2.6 Limitations of the methodology

The evidence base is a convenience sample and may be biased toward open-access and widely indexed sources. Abstract-level verification can miss qualifications stated in the full texts. Coverage of 2019-2026 work is limited and should be extended before submission. A future systematic update could use a documented search string in at least two bibliographic databases, for example (ultra-high performance concrete OR UHPC OR UHPFRC) AND (compressive OR flexural OR flexure OR “stress-strain” OR toughness) with publication years 2019-2026, followed by recorded screening; this string is a proposal and has not been run. [AUTHOR INPUT REQUIRED: whether to perform and report such a search.]

3. UHPC: DEVELOPMENT, MATERIALS AND MICROSTRUCTURE

3.1 Development of UHPC

The theoretical basis of UHPC lies in particle-packing optimization. Packing models allow the selection of aggregate and powder fractions that minimize voids and therefore the water and paste needed for

workability (De Larrard & Sedran, 1994). Richard and Cheyrezy (1995) combined this principle with several measures: elimination of coarse aggregate to improve homogeneity, use of silica fume and fine quartz powder, a very low water-to-binder ratio enabled by high-range water reducers, optional thermal treatment, and steel fiber reinforcement. These principles remain the basis of most UHPC formulations.

European research, notably in Germany and France, developed design recommendations and applications through the 1990s and 2000s (Schmidt & Fehling, 2005; AFGC/SETRA, 2013; Fehling et al., 2014). In North America, the FHWA carried out extensive characterization of a proprietary UHPC for bridge use, producing material property data, structural tests and design-oriented reports (Graybeal, 2006; Graybeal, 2007; Graybeal, 2008; Russell & Graybeal, 2013). More recently, studies have sought UHPC with locally available materials and without special heat treatment (Wille et al., 2011a; Wille et al., 2012; Lande & Thorstensen, 2021), with lower cost (Meng et al., 2017) and with reduced cement content (Yu et al., 2015). A state-of-the-art review published in 2022 collects work on composition, mechanical and durability properties and design considerations (Ullah et al., 2022).

3.2 Constituents and mix design

Published reviews describe UHPC as typically composed of Portland cement, silica fume, fine quartz sand and/or quartz powder, a polycarboxylate-type high-range water reducer, water and, in most cases, discontinuous steel fibers (Shi et al., 2015; Yu et al., 2014). The typical constituents and their functions are summarized in Table 1.

Table 1. Major constituents of UHPC and their functions.

Constituent material	Typical role in UHPC	Contribution to performance
Portland cement	Principal binder; used in much larger quantity than in conventional concrete (Shi et al., 2015)	Forms the hydrated matrix; high content with low water-to-binder ratio gives a dense, strong paste, and unhydrated grains may act as fine filler (Wang et al., 2015)
Silica fume	Ultrafine filler and pozzolan	Fills voids between cement grains and reacts pozzolanically, densifying the matrix (Richard & Cheyrezy, 1995; Shi et al., 2015)
Fine/quartz aggregate	Fine granular skeleton in place of coarse aggregate	Reduces heterogeneity and interfacial weak zones; grading is chosen by packing optimization (De Larrard & Sedran, 1994; Yu et al., 2014)
Superplasticizer	High-range water reducer, typically polycarboxylate-based	Allows flowable placement at very low water-to-binder ratio, which also supports fiber dispersion (Shi et al., 2015; Yu et al., 2014)
Supplementary cementitious materials	Partial cement replacement and additional fine filler	May lower cement content and improve packing; effect depends on type and dosage (Yu et al., 2014; Yu et al., 2015)
Steel fibers	Discontinuous reinforcement, most commonly steel	Bridge cracks, giving tensile, flexural and post-cracking capacity; length, content and orientation govern the response (Abbas et al., 2015a; Russell & Graybeal, 2013; Yoo & Banthia, 2016)
Water	Medium for hydration and workability, kept very low	Low water-to-binder ratio leaves less free water and fewer voids in the matrix (Graybeal & Hartmann, 2003)

Note. The typical constituents are those reported in the reviews cited; proportions vary widely between studies and are not generalized here.

Mix design proceeds by (i) selecting a target particle-packing curve or model, (ii) fixing a low water-to-binder ratio, (iii) tuning superplasticizer dosage for flowability, and (iv) choosing fiber type and volume fraction for the desired tensile and flexural performance. Yu et al. (2014) describe a mix-design approach based on optimized packing, and Wille et al. (2011a) show that UHPC with high compressive strength can be obtained with a simplified procedure and conventional materials. Numerical mix proportions vary

widely between sources and are not generalized here. The review of Ullah et al. (2022) concluded that the best UHPFRC mixtures it surveyed combined steel fiber contents of 2-3% with water-to-cement ratios of 0.2-0.3; this is a conclusion of a review of other studies and not a design rule. Table 2 summarizes how the principal mix and processing variables affect compressive and flexural behavior; the underlying studies are discussed in Sections 5 and 6.

Table 2. Factors affecting the mechanical behavior of UHPC.

Factor	Effect on compressive behavior	Effect on flexural behavior	Engineering significance
Water-to-binder ratio	Lower ratios are associated with a denser matrix and higher strength (Shi et al., 2015; Yu et al., 2014)	Indirect, through matrix strength and fiber-matrix bond (author interpretation; Yoo & Banthia, 2016)	Must be balanced against flowability and fiber dispersion
Fiber volume fraction	Mechanical properties, including compressive, increased with dosage from 1% to 6% in one study (Abbas et al., 2015a); not studied separately by Graybeal (2007); no influence of fiber content in another study (Lande & Thorstensen, 2021)	Higher content gave stiffer post-cracking response and higher peak load (1% to 2%; Russell & Graybeal, 2013); flexural properties increased with dosage (Abbas et al., 2015a)	Raises cost and can impair workability; dosage is chosen for target ductility and capacity
Fiber geometry	Longer fibers (6, 10 and 15 mm at 2.5% by volume) improved compressive strength and modulus in one study (Wei et al., 2021)	Short fibers gave better flexural properties at similar volume (Abbas et al., 2015a), whereas longer fibers raised flexural strength and energy absorption in another study (Yoo et al., 2016a); fiber length influenced orientation (Yoo et al., 2016a)	Results differ between studies; optimum depends on matrix, specimen size and casting
Curing condition	Thermal treatment can raise strength (Richard & Cheyrezy, 1995; Wang et al., 2015); strength-gain rate of a field UHPC depended on curing temperature (Graybeal & Stone, 2012)	Affects matrix quality and thus cracking and bond (Wang et al., 2015; Yoo & Banthia, 2016)	Curing must be reported and matched to precast or field use
Particle packing	Denser packing reduces voids and supports strength (De Larrard & Sedran, 1994; Yu et al., 2014); flow-table spread indicates packing (Wille et al., 2011a)	Indirect, through matrix quality and bond (author interpretation)	Basis of mix design
Matrix composition	Type of cement, silica fume, sand and HRWR influenced strength (Wille et al., 2011a); SCMs can reduce cement content (Yu et al., 2015)	Affects cracking strength and bond (author interpretation)	Trade-off between cement reduction and early strength
Aggregate characteristics	Fine aggregate replaces coarse aggregate, reducing heterogeneity (Richard & Cheyrezy, 1995)	[AUTHOR INPUT REQUIRED: verified data on aggregate size relative to fiber length]	Maximum particle size influences homogeneity and fiber dispersion (author interpretation)

Note. HRWR = high-range water reducer; SCM = supplementary cementitious material. Entries marked author interpretation are not direct findings of the cited study.

3.3 Microstructure

The microstructure of UHPC is characterized by low porosity, a dense calcium-silicate-hydrate-rich matrix, a high proportion of unhydrated cement particles that act as micro-aggregates, and an improved interfacial transition zone around fine aggregate and fibers, as discussed in reviews of hydration and microstructure (Wang et al., 2015; Shi et al., 2015). Thermal treatment accelerates hydration and

pozzolanic reaction and can refine the pore structure, which is one reason curing regime strongly influences strength (Richard & Cheyrezy, 1995; Wang et al., 2015). The dense matrix increases the matrix tensile strength and bond with fibers, which in turn increases the stress that fibers can carry (Yoo & Banthia, 2016). Figure 1 contrasts the conceptual microstructures of conventional concrete and UHPC.

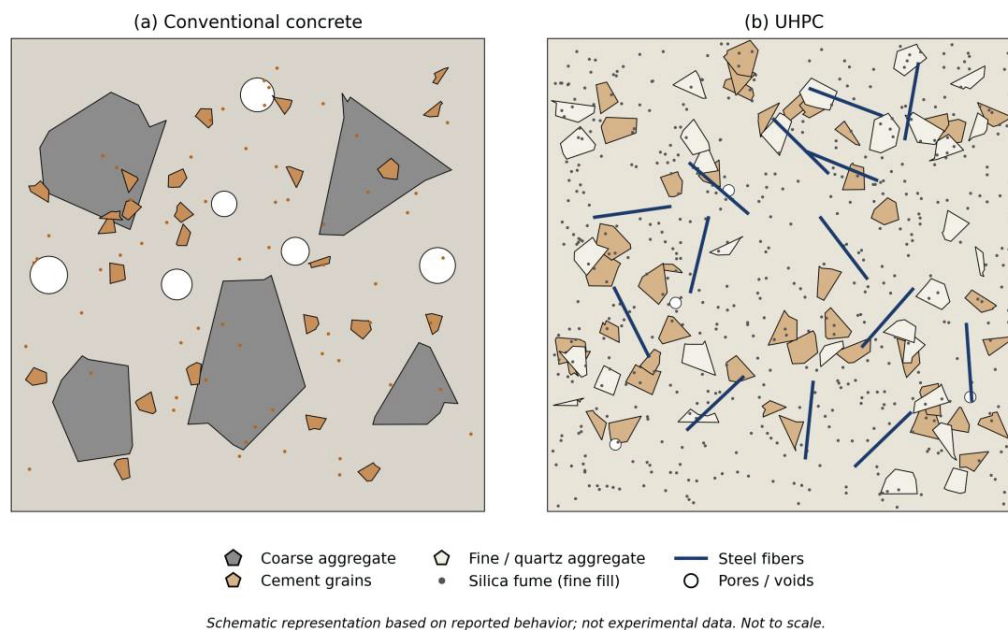


Figure 1. Conceptual composition and microstructure of (a) conventional concrete and (b) UHPC, showing coarse aggregate and larger voids in (a) and cement grains, silica fume, fine/quartz aggregate, steel fibers and a dense, low-porosity matrix in (b). Schematic representation based on reported behavior; not experimental data; not to scale.

4. TEST METHODS, STANDARDS AND QUANTITIES USED IN THE LITERATURE

This section describes how the properties discussed in later sections are defined and measured. It is a description of established methods and of the quantities reported in the reviewed studies; no tests were performed for this paper.

ASTM C1856/C1856M is the standard practice for fabricating and testing specimens of UHPC. Its scope covers UHPC with a specified compressive strength of at least 120 MPa, a nominal maximum aggregate size below 5 mm and a flow between 200 and 250 mm on the modified flow table, and it includes procedures for fresh and hardened specimens (ASTM International, 2024). Conventional methods, modified for UHPC by that practice, are widely used for the individual properties: ASTM C39/C39M for compressive strength of cylinders, ASTM C469/C469M for modulus of elasticity, ASTM C78/C78M for flexural strength by third-point loading, and ASTM C1609/C1609M for flexural performance of fiber-reinforced concrete including post-peak response. Specimen size and shape influence reported strengths (Graybeal & Davis, 2008; Riedel et al., 2019), and the load rate used in the FHWA compression studies was about 1 MPa/s (Graybeal, 2007; Graybeal & Stone, 2012).

Compressive strength is the maximum load divided by the cross-sectional area:

$$f_c = \frac{P_{\max}}{\xi} \quad (1)$$

where f_c is compressive strength (MPa), $P_{\max}$ is the maximum load (N) and ξ is the cross-sectional area of the specimen (mm²).

Flexural strength (modulus of rupture) for a beam failing within the middle third of the span under third-point loading is

$$R = \frac{P L}{b d^2} \quad (2)$$

where R is the modulus of rupture (MPa), P is the maximum load (N), L is the span length (mm), b is the average beam width (mm) and d is the average beam depth (mm) (as defined in ASTM C78/C78M).

The chordal modulus of elasticity from a compression test follows ASTM C469/C469M:

$$E = \frac{S_2 - S_1}{\varepsilon_2 - 0.000050} \quad (3)$$

where E is the chordal modulus (MPa), S_2 is the stress at 40% of ultimate strength, S_1 is the stress corresponding to a longitudinal strain of 50 microstrain, and ε_2 is the longitudinal strain at S_2 .

For fiber-reinforced beams, ASTM C1609/C1609M defines the residual strength at a net deflection of $L/150$ and the toughness as the area under the load-deflection curve up to that deflection:

$$f_{150}^D = \frac{P_{150}^D L}{b d^2} \quad (4)$$

where f_{150}^D is the residual strength at net deflection $L/150$ (MPa), P_{150}^D is the corresponding residual load (N), and L, b, d are as in Eq. (2).

Engineering stress and strain in compression are

$$\sigma = \frac{P}{\xi}, \quad \varepsilon = \frac{\Delta L}{L_0} \quad (5)$$

where σ is stress (MPa), P is applied load (N), λ is cross-sectional area (mm²), ε is axial strain (dimensionless), ΔL is the measured change in gauge length (mm) and L_0 is the original gauge length (mm).

These formulations are the established forms in the cited standards; their applicability to UHPC specimen sizes, fiber lengths and strength levels should be checked against the current standard text. Different studies use different toughness indices and notched or unnotched beams, which limits quantitative comparison (Section 8.3).

5. COMPRESSIVE BEHAVIOR: EVIDENCE AND SYNTHESIS

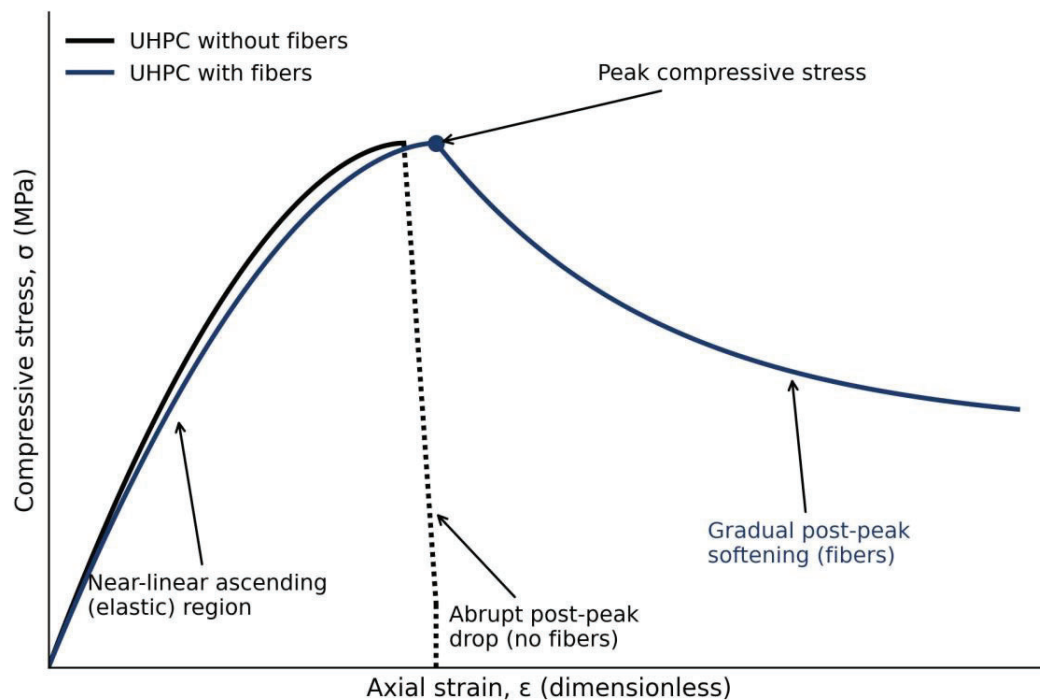
5.1 Strength levels, curing and matrix composition

UHPC reaches compressive strengths far above those of conventional concrete. Graybeal and Hartmann (2003) reported strengths that could exceed about 200 MPa for the FHWA-studied material, and Graybeal (2008) used a UHPC of 193 MPa in a prestressed girder. Wille et al. (2011a) produced a UHPC exceeding 200 MPa from commercially available U.S. materials without heat treatment, pressure or special mixing equipment, and proposed the flow-table spread as a quick guide to packing density and strength. Lande and Thorstensen (2021) obtained a compressive strength of 166 MPa and a modulus of 46 GPa with constituents found in southern Norway.

Curing influences strength development. Thermal treatment can raise strength (Richard & Cheyrezy, 1995; Wang et al., 2015), and the strength gain of a rapid-strengthening UHPC formulation depended on the curing environment (Graybeal & Stone, 2012). A 2022 review of microwave, autoclave, carbon, steam, electric, ambient and water curing found that all methods gave satisfactory compressive strengths and that a single optimum regime cannot be specified, because curing temperature, duration and materials all matter (Hamada et al., 2022). A lower water-to-binder ratio is associated with a denser matrix and higher strength provided workability and fiber dispersion are maintained (Shi et al., 2015; Yu et al., 2014).

5.2 Stress-strain behavior, modulus and the role of fibers

Graybeal (2007) established the compressive stress-strain behavior and modulus of a UHPFRC reinforced with 13 mm steel fibers by cylinder tests and compared the results with equations developed for normal and high-strength concrete; the effect of the fibers on compressive properties was not studied separately. Evidence on the fiber effect elsewhere is not uniform. Abbas et al. (2015a) reported that mechanical properties increased with steel fiber dosage over 1% to 6% by volume. Wei et al. (2021), using fibers of 6, 10 and 15 mm at a fixed 2.5% dosage, found that longer fibers improved both compressive strength and elastic modulus. By contrast, Lande and Thorstensen (2021) found that compressive strength and modulus were not influenced by fiber content in their mixes. Section 8.2 discusses possible reasons. The typical response is sketched conceptually in Figure 2; the sketch is not drawn from any dataset.



Schematic representation based on reported behavior; not experimental data.

Figure 2. Typical compressive stress-strain response of UHPC without and with fibers, showing the near-linear ascending region, peak stress and post-peak behavior. Schematic representation based on reported behavior; not experimental data. Axes are intentionally unscaled.

5.3 Specimen size, shape and test method

Graybeal and Davis (2008) tested 51, 76 and 102 mm cylinders alongside 51, 70.7 and 100 mm cubes of UHPFRC with strengths of 80 to 200 MPa, and concluded that the 76 mm cylinder and the 70.7 mm and 102 mm cubes could substitute for the standard 102 mm cylinder, favoring the 70.7 mm cube where machine capacity or cylinder end preparation constrains testing. Riedel et al. (2019) examined mixtures without fibers and reported that, compared with ordinary-performance and high-performance concrete, the effect of specimen geometry on compressive strength is very small for UHPC. These findings suggest that the choice of specimen can matter less for fiber-free UHPC but should still be reported, and that the conclusions for fiber-reinforced material need separate confirmation.

5.4 Summary of compressive evidence

Table 3 summarizes selected studies. Findings are taken from abstracts or reports, and limitations are the author's assessment from the information available.

Table 3. Compressive behavior of UHPC reported in selected studies.

Author(s) and year	Material / mix	Fiber type and content	Curing	Specimen / test	Key findings	Limitations	Source
Graybeal & Hartmann (2003)	Proprietary FHWA UHPC; very low w/b	Steel; content [AUTHOR INPUT REQUIRED]	[AUTHOR INPUT REQUIRED]	Material property testing	Strength could exceed about 200 MPa; tensile strength about 7-14 MPa; durability exceeded HPC	Read from an FHWA-hosted summary; details not available	TRB 82nd Annual Meeting
Graybeal (2007)	UHPC, high cement and silica fume content	Steel, 13 mm; content not stated	[AUTHOR INPUT REQUIRED]	Cylinders, about 1 MPa/s, axial gauges	Stress-strain behavior and modulus established; compared with equations for normal and high-strength concrete	Fiber effect not studied separately; single proprietary mix	ACI Mater. J. 104(2)
Graybeal & Davis (2008)	UHPC, 80-200 MPa	Fiber-reinforced (type not stated in abstract)	[AUTHOR INPUT REQUIRED]	51, 76, 102 mm cylinders; 51, 70.7, 100 mm cubes	76 mm cylinder and 70.7 and 102 mm cubes judged acceptable substitutes for the 102 mm cylinder	Details of ratios not available at abstract level	ACI Mater. J. 105(6)
Wille et al. (2011a)	Commercially available U.S. materials; cement, silica fume, sand, HRWR varied	Steel fibers (per keywords)	No heat treatment, pressure or special mixer	Compression; flow-table spread	Strength above 200 MPa; spread proposed as proxy for packing density and strength	Fiber effect not the focus; materials-specific	ACI Mater. J. 108(1)
Abbas et al. (2015a)	UHPC with varied fiber length and dosage	Steel, 8, 12, 16 mm at 1%, 3%, 6% by volume	[AUTHOR INPUT REQUIRED]	Compressive, splitting tensile, flexural; chloride exposure	Properties increased with dosage; no degradation after chloride exposure	Curing and specimen size not available at abstract level	Constr. Build. Mater. 75
Graybeal & Stone (2012)	Rapid-strengthening UHPC for field connections	Discrete steel fibers	Strength gain depended on curing temperature	Compressive strength and modulus gain at about 1 MPa/s	Rate of property development depended on curing environment	Specific proprietary formulation	FHWA-HRT-12-064
Riedel et al. (2019)	OPC, HPC and fiber-free UHPC; mean cylinder strengths 30-200 MPa	None	Standardized (details in source)	Specimens of different shapes and sizes	Geometry effect on strength very small for UHPC compared with OPC and HPC	Fiber-free mixtures only	ACI Mater. J. 116(6)
Lande & Thorstensen (2021)	Locally produced UHPC, southern Norway; nine mixes	Steel fibres; content, type and hybrid combinations	[AUTHOR INPUT REQUIRED]	231 specimens; digital image correlation	166 MPa and 46 GPa, not influenced by fibre content	Single region; fiber ranges not stated at abstract level	Nordic Concr. Res. (2021)
Wei et al. (2021)	UHPC, four mixes	Straight steel, 6, 10, 15 mm, 0.2 mm diameter, 2.5% by volume	[AUTHOR INPUT REQUIRED]	Quasi-static compression and flexure; impact beams	Longer fibers improved compressive strength and modulus	Single dosage; authors list to verify	Eng. Struct. 245
Hamada et al. (2022)	Review of curing methods	Not applicable	Microwave, autoclave, carbon, steam, electric, ambient, water	Review of compressive strength studies	All methods satisfactory; no single peak regime can be specified	Compressive strength only; secondary evidence	Case Stud. Constr. Mater. 17

Note. HPC = high-performance concrete; OPC = ordinary-performance concrete; HRWR = high-range water reducer; w/b = water-to-binder ratio; FHWA = Federal Highway Administration; TRB = Transportation Research Board. Findings are at abstract or report level. [AUTHOR INPUT REQUIRED] marks details to be taken from the original papers.

6. FLEXURAL AND POST-CRACKING BEHAVIOR: EVIDENCE AND SYNTHESIS

6.1 Flexural strength, toughness and fiber content

Flexural tests capture both the cracking strength and the post-cracking response. Graybeal (2008) tested a full-scale prestressed UHPC I-girder without mild steel reinforcement, examined cracking, stiffness and moment capacity, developed a relationship between tensile strain and crack spacing, and proposed a flexural design philosophy. The FHWA state-of-the-art report notes that increasing fiber content from 1% to 2% produced a stiffer post-cracking response and higher peak loads in the beam tests it reviews (Russell & Graybeal, 2013). Abbas et al. (2015a) found that flexural properties increased with fiber

dosage over 1% to 6%, and in tunnel-lining segments (Abbas et al., 2015b) load capacity increased linearly with dosage. Yoo and Yoon (2015) reported that 2% by volume of steel fibers raised the load capacity of reinforced UHPC beams but reduced ductility, an important trade-off for design.

Strain-hardening UHPC can exhibit deflection hardening and multiple cracking in flexure (Naaman & Reinhardt, 2006; Wille et al., 2011b), and the tensile response of hybrid steel and non-metallic fiber systems has been examined for toughness and cost benefits (Li & Deng, 2021). A review of 2016 covers flexural behavior in relation to fiber type, content and curing (Yoo & Banthia, 2016).

6.2 Fiber length, geometry and hybridization

Evidence on fiber length is mixed. Abbas et al. (2015a) found that, at similar volume, short fibers gave better flexural properties, and Abbas et al. (2015b) found that shorter fibers gave higher cracking and peak loads in segments while longer fibers gave more ductile post-peak softening. Yoo et al. (2016a) reported that longer fibers raised flexural strength and energy absorption with little effect on first-cracking properties. Yoo et al. (2018) found that long straight and twisted fibers improved quasi-static flexural performance, especially at large deflections. Hybrid systems are reported to help: in the work of Wei et al. (2021), a mixture with hybrid long and short fibers reached a flexural strength and fracture energy 21.84% and 20.13% greater than a single-long-fiber mixture, and Lande and Thorstensen (2021) found the highest flexural tensile strength with micro straight fibers alone or in a 50% combination with macro hooked-end fibers, with a potential cost reduction of about 30%.

6.3 Fiber distribution and orientation

Fiber orientation emerges as a dominant source of variability. The FHWA review stresses that post-cracking response is highly sensitive to fiber dispersion and orientation (Russell & Graybeal, 2013). Barnett et al. (2010) showed that casting method changed fiber alignment in round panels, with fibers aligning perpendicular to the flow, and that panels poured from the centre were significantly stronger because more fibers bridged the radial cracks. Yoo et al. (2016b), who quantified orientation by image analysis, found that fibers better aligned with the tensile direction gave higher flexural strength, deflection capacity and toughness under quasi-static loading, with no obvious difference in first-cracking properties. Kang et al. (2011) examined fiber distribution characteristics and flexural strength. Li et al. (2020) used a magnetic probe on UHPFRC plates and found a mean orientation angle of 45.60 degrees and a correlation between peak flexural strength and the product of fiber volume content and the cosine of the orientation angle. Maryamh et al.

6.4 Summary of flexural evidence

Table 4 summarizes selected studies. Findings are at abstract or report level, and limitations are the author's assessment.

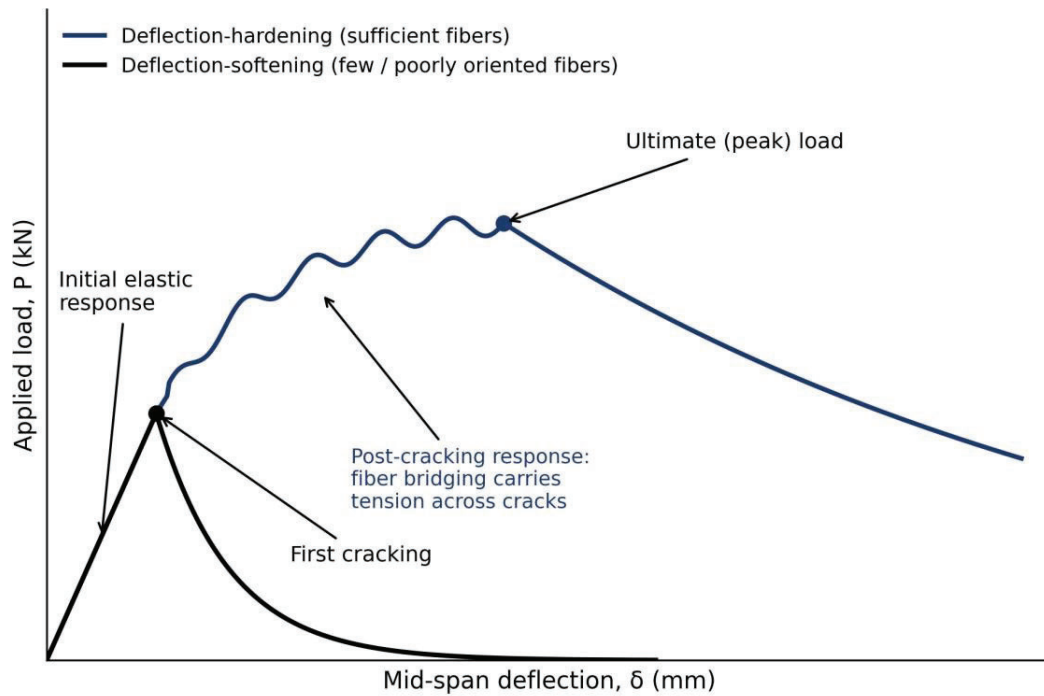
Table 4. Flexural behavior of UHPC reported in selected studies.

Author(s) and year	Material / mix	Fiber type and content	Curing	Specimen / test	Key findings	Limitations	Source
Graybeal (2008)	Steel-fiber UHPC, 193 MPa	Steel; content [AUTHOR INPUT REQUIRED]	[AUTHOR INPUT REQUIRED]	24.4 m prestressed I-girder, 26 strands, no mild steel	Tensile strain-crack spacing relation; flexural design philosophy	Single girder; proprietary UHPC	J. Bridge Eng. 13(6)

Meade & Graybeal tests as reported by Russell & Graybeal (2013)	Steel-fiber UHPC	Steel; 0%, 1%, 2% by volume	[AUTHOR INPUT REQUIRED]	Sixteen 152 x 381 mm beams, four-point bending, 4.88 m span; reinforcement 0-1.00%	1% to 2% fibers: stiffer post-cracking response, higher peak load; no crushing noted	Secondary report; scale of specimens	FHWA-HRT-13-060
Abbas et al. (2015a)	UHPC, varied fiber length and dosage	Steel, 8, 12, 16 mm; 1%, 3%, 6%	[AUTHOR INPUT REQUIRED]	Flexural strength tests	Short fibers better at similar volume; properties rose with dosage	Details at abstract level	Constr. Build. Mater. 75
Abbas et al. (2015b)	UHPC segments	Steel, various lengths; dosages not stated	[AUTHOR INPUT REQUIRED]	1/3-scale tunnel-lining segments; flexural and edge-point load	Short fibers: higher cracking and peak loads; long fibers: more ductile post-peak; capacity linear with dosage	Segment scale; volume and pages to verify	Eng. Struct. (2015)
Yoo & Yoon (2015)	UHPC beams with rebars	Smooth (13, 19.5, 30 mm), twisted (30 mm); 2%	[AUTHOR INPUT REQUIRED]	Ten beams; rebar ratios 0.94% and 1.50%	About 27-54% higher capacity, 13-73% lower ductility with 2% fibers	Reinforced beams only	Eng. Struct. 102
Yoo et al. (2016a)	UHPC	Steel, three lengths, same diameter; content not stated	[AUTHOR INPUT REQUIRED]	Flexure; image analysis; finite elements	Longer fibers raised strength and energy absorption; orientation affected by length	Content not available at abstract level	Compos. Struct. 147
Yoo et al. (2016b)	UHPFRC	Steel [AUTHOR INPUT REQUIRED]	[AUTHOR INPUT REQUIRED]	Two placement methods and sizes; quasi-static and impact; image analysis	Better alignment: higher strength, deflection capacity, toughness	Details at abstract level	Compos. Struct. 157
Yoo et al. (2018)	UHPC beams	Straight (aspect ratios 65, 97.5, 100) and twisted (100)	[AUTHOR INPUT REQUIRED]	Quasi-static and impact beams	Long straight and twisted fibers improved large-deflection behavior	Content not stated	Cem. Concr. Compos. 86
Barnett et al. (2010)	UHPFRC round panels	Steel; content [AUTHOR INPUT REQUIRED]	[AUTHOR INPUT REQUIRED]	Panels cast in different ways; resistivity; CT; flexure	Centre-poured panels significantly stronger; fibers align perpendicular to flow	Pre-2019; panel geometry	Mater. Struct. 43(7)
Li et al. (2020)	UHPFRC plates	Straight steel fibers	[AUTHOR INPUT REQUIRED]	Plates; magnetic probe; small flexural specimens	Peak flexural strength correlates with fiber volume x cosine of orientation angle	Plate-specific; calibration	Materials 13(22)
Maryamh et al. (2021)	UHPFRC	Steel; varied diameter and volume fraction	[AUTHOR INPUT REQUIRED]	Casting from side or middle; micro CT; four-point bending	Results explained by fiber-system characteristics from images	Details at abstract level	Struct. Concr. 22(1)
Wei et al. (2021)	UHPC	Straight steel 6, 10, 15 mm; 2.5%	[AUTHOR INPUT REQUIRED]	Notched three-point bending; impact beams (2000 x 168 x 168 mm)	Hybrid long and short fibers: +21.84% strength, +20.13% fracture energy over single long	Single dosage; authors list to verify	Eng. Struct. 245
Lande & Thorstensen (2021)	Locally produced UHPC	Steel fibres, content, type, hybrid	[AUTHOR INPUT REQUIRED]	231 specimens; DIC	Highest flexural tensile strength: micro straight alone or 50% with macro hooked	Single region; ranges not stated	Nordic Concr. Res. (2021)

Note. UHPFRC = ultra-high performance fiber-reinforced concrete; DIC = digital image correlation; CT = computed tomography. Percent values are reproduced only where stated in the cited abstracts or reports. [AUTHOR INPUT REQUIRED] marks details to be taken from the original papers.

Figure 3 sketches the typical flexural load-deflection response conceptually; it is not drawn from any dataset.

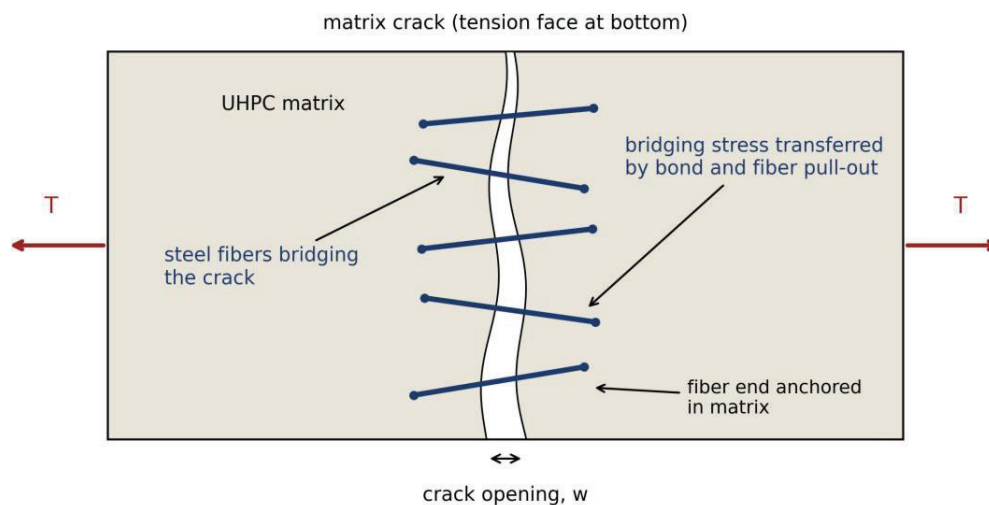


Conceptual representation; schematic representation based on reported behavior; not experimental data.

Figure 3. Typical flexural load-deflection response of UHPC beams, showing initial elastic response, first cracking, post-cracking response with fiber bridging and ultimate load for deflection-hardening and deflection-softening behavior.
 Conceptual representation; schematic representation based on reported behavior; not experimental data.

7. FAILURE MECHANISMS

The mechanisms below are the author's synthesis of the behavior described in the cited sources and of general understanding of fiber-reinforced cementitious composites. Figure 4 shows the fiber-bridging mechanism that underlies the tensile and flexural mechanisms, and Table 5 summarizes the mechanisms by loading condition.



Schematic of the fiber-bridging mechanism; not to scale; not experimental data.

Figure 4. Crack propagation and fiber bridging in UHPC: a matrix crack of opening w is crossed by steel fibers that transfer tensile stress through bond and pull-out. Schematic representation; not to scale; not experimental data.

Compressive failure. In UHPC without fibers, the dense homogeneous matrix stores significant elastic energy, and once lateral tensile strains cause axial splitting the failure is sudden. Fibers restrain lateral dilation and crack opening, leading to a more gradual post-peak response (author synthesis).

Tensile cracking. Cracking begins when the matrix tensile strength is reached at a flaw or at the tension face of a beam. The high matrix strength and high bond mean that cracks form at higher stress than in conventional concrete (Yoo & Banthia, 2016).

Fiber bridging. After a crack forms, fibers crossing it carry tensile stress through bond and pull-out, limiting crack opening. Whether the composite can carry more load than at first cracking depends on whether the bridging stress exceeds the cracking stress, which is the criterion distinguishing strain-hardening from strain-softening behavior (Naaman & Reinhardt, 2006).

Crack propagation. In strain-hardening material, bridging allows new cracks to form before any single crack localizes, producing multiple fine cracks (Habel et al., 2006; Wille et al., 2014). In strain-softening material, one crack localizes and opens.

Post-cracking behavior. The post-cracking response is governed by fiber content, orientation, length and bond, and is highly sensitive to fiber dispersion and orientation (Russell & Graybeal, 2013; Yoo et al., 2016b).

Flexural failure. Flexural failure occurs by localization of a dominant crack followed by fiber pull-out or fiber rupture, or, in members with reinforcement, by yielding or rupture of reinforcement, depending on the section design (Graybeal, 2008; Russell & Graybeal, 2013).

Table 5. Failure mechanisms of UHPC under compressive and flexural loading.

Loading condition	Failure mechanism	Crack development	Role of fibers	Typical observation
Compression	Axial splitting driven by lateral tensile strain, followed by crushing (author synthesis)	Vertical splitting cracks near peak load; without fibers, development is rapid (author synthesis)	Restrain lateral dilation and crack opening, leading to more gradual post-peak response (author synthesis; not studied separately by Graybeal, 2007)	Sudden failure without fibers; more gradual softening with fibers [AUTHOR INPUT REQUIRED: own test observations]
Flexure	Tensile cracking at the tension face when the matrix tensile strength is reached	Single localizing crack (strain-softening) or multiple cracks (strain-hardening) (Naaman & Reinhardt, 2006; Wille et al., 2014); crack spacing related to tensile strain in girders (Graybeal, 2008)	Carry stress across cracks; fiber length had little effect on first-cracking properties but raised strength and energy absorption (Yoo et al., 2016a)	No concrete crushing noted in rectangular beam tests reviewed by Russell & Graybeal (2013)
Post-cracking flexure	Localization of a dominant crack, then fiber pull-out or rupture; reinforcement yielding in reinforced members	Crack widening after localization, preceded by multiple cracking in strain-hardening material	Transfer tension by bond and pull-out; response sensitive to dispersion and orientation (Russell & Graybeal, 2013); fibers raised capacity but reduced ductility in reinforced beams (Yoo & Yoon, 2015)	Longer fibers gave more ductile post-peak softening in tunnel-lining segments (Abbas et al., 2015b)

Note. Entries marked author synthesis combine general understanding of fiber-reinforced cementitious composites and are not direct findings of a single cited study.

8. CRITICAL SYNTHESIS

8.1 Points of agreement

The reviewed studies agree on several points. First, compressive strengths above about 150 MPa, and in several cases about 200 MPa, are attainable, including with locally available materials and without heat treatment (Wille et al., 2011a; Lande & Thorstensen, 2021). Second, fibers govern tensile, flexural and post-cracking behavior, and higher fiber content generally improves flexural capacity and post-cracking stiffness within the ranges studied (Russell & Graybeal, 2013; Abbas et al., 2015a; Yoo & Yoon, 2015). Third, fiber orientation and distribution have a large influence on flexural response, as shown with several different measurement techniques (Barnett et al., 2010; Yoo et al., 2016b; Li et al., 2020; Maryamh et al., 2021). Fourth, specimen geometry has only a small influence on the compressive strength of fiber-free UHPC (Riedel et al., 2019), while curing has a strong but mix-dependent effect (Hamada et al., 2022).

8.2 Points of disagreement and possible reasons

Fiber effect on compressive behavior. Abbas et al. (2015a) report increasing mechanical properties with fiber dosage, Wei et al. (2021) report improvement with fiber length, whereas Lande and Thorstensen (2021) report no influence of fiber content on compressive strength and modulus. Possible reasons, which are author interpretation, include differences in fiber dosage range, matrix packing and water-to-binder ratio, curing, specimen size, and whether fibers alter air content or compaction. The studies are not directly comparable, and the full texts should be consulted before drawing quantitative conclusions.

Optimal fiber length and combination. Short fibers performed better at similar volume in one study (Abbas et al., 2015a), whereas longer fibers raised flexural strength and energy absorption in another (Yoo et al., 2016a), and hybrid combinations performed best in two further studies (Wei et al., 2021;

Lande & Thorstensen, 2021). Plausible reasons (author interpretation) are that the optimum depends on the matrix and bond, on the size of the specimen relative to fiber length, on fiber orientation produced by casting, on whether beams or notched specimens are used, and on whether the stage evaluated is first cracking, peak load or large-deflection toughness. The consistency of the finding that first-cracking properties are little affected by fiber length (Yoo et al., 2016a; Yoo et al., 2016b) supports the view that differences arise mainly after cracking.

Ductility versus capacity. Fibers raised the capacity of reinforced beams but lowered their ductility in one study (Yoo & Yoon, 2015), which contrasts with the general view of fibers as ductility enhancers; the difference is plausibly related to how fibers change the crack pattern in reinforced members (author interpretation).

8.3 Methodological limitations of the evidence

Several limitations restrict comparison between studies. Specimen geometries, beam sizes, notched versus unnotched tests and toughness indices differ widely. Fiber orientation is reported in only some studies, although it can dominate flexural response. Many studies are single-laboratory programmes on a single matrix, so interactions between matrix and fiber effects cannot be separated. Curing regimes vary and are sometimes incompletely reported. Loading rates are often not stated, and reliable data on rate effects in compression and flexure were not identified in this review. The evidence tables in this paper are limited to abstract-level information, which itself is a limitation of this review.

8.4 Comparison with conventional concrete and HPC

Table 6 gives a qualitative comparison of conventional concrete, HPC and UHPC, and Figure 5 shows the same comparison graphically. Strength values are included only where a source is cited; entries for conventional concrete and HPC are the author's synthesis.

Table 6. Qualitative comparison of conventional concrete, HPC and UHPC.

Property	Conventional concrete	High-performance concrete (HPC)	UHPC
Matrix density	Lowest of the three; coarse aggregate and larger voids (see Figure 1)	Denser than conventional concrete	Highest; optimized packing and very low water-to-binder ratio (De Larrard & Sedran, 1994; Richard & Cheyrezy, 1995)
Compressive strength	Lowest of the three	Intermediate	Highest; strengths of about 200 MPa or more reported (Graybeal & Hartmann, 2003; Wille et al., 2011a)
Flexural/tensile behavior	Low tensile capacity; brittle after cracking	Improved tensile capacity but generally limited ductility	Highest; tensile strength of about 7-14 MPa reported for the FHWA-studied UHPC (Graybeal & Hartmann, 2003); strain-hardening possible (Naaman & Reinhardt, 2006; Wille et al., 2014)
Crack control	Limited	Moderate	Fibers bridge cracks; multiple fine cracking in strain-hardening mixtures (Habel et al., 2006; Wille et al., 2014)
Durability	Baseline	Improved relative to conventional concrete	Durability properties reported to significantly exceed HPC (Graybeal & Hartmann, 2003); no loss of mechanical properties after chloride exposure in one study (Abbas et al., 2015a)
Permeability	Highest of the three	Lower	Lowest; dense, low-porosity matrix (Shi et al., 2015; Wang et al., 2015)
Fiber reinforcement	Not typically used	Not typically used	Steel fibers typical (Russell & Graybeal, 2013)

Property	Conventional concrete	High-performance concrete (HPC)	UHPC
Typical applications	General building and civil construction	Structures requiring higher strength or durability (author synthesis)	Prestressed bridge girders (Graybeal, 2008); field-cast connections between prefabricated elements (Graybeal & Stone, 2012); precast tunnel-lining segments (Abbas et al., 2015b)

Note. HPC = high-performance concrete; UHPC = ultra-high performance concrete; FHWA = Federal Highway Administration. The comparison is qualitative; strength values are given only where a source is cited, and entries for conventional concrete and HPC are author synthesis.

	Conventional concrete	High-performance concrete (HPC)	UHPC
Compressive strength	Lowest	Intermediate	Highest
Tensile / flexural performance	Lowest	Intermediate	Highest
Durability (resistance to ingress)	Lowest	Intermediate	Highest
Crack control	Lowest	Intermediate	Highest
Matrix density / microstructure	Lowest	Intermediate	Highest

Qualitative, relative ranking only (no measured values); based on general trends reported in the literature.

Figure 5. Conceptual comparison of conventional concrete, high-performance concrete (HPC) and UHPC for compressive strength, tensile/flexural performance, durability, crack control and matrix density. Qualitative relative ranking only, based on general trends reported in the literature; not experimental data.

9. STRUCTURAL APPLICATIONS AND SUSTAINABILITY

9.1 Structural applications

Statements below combine verified findings and author interpretation, and application-specific claims should be supported by project-specific references to be added.

- **Bridges:** Graybeal (2008) demonstrated that a prestressed UHPC girder could be built without mild steel reinforcement and tested to capacity, and the FHWA report reviews bridge applications (Russell & Graybeal, 2013).
- **Field-cast connections:** a rapid-strengthening UHPC formulation was developed for connections between prefabricated elements, with strength gain depending on curing temperature (Graybeal & Stone, 2012).
- **Tunnel linings:** UHPFRC lining segments were tested with varying fiber lengths and dosages (Abbas et al., 2015b).

- **Precast components and thin elements:** high flowability and tensile capacity allow slender sections, but fiber orientation control is critical (Russell & Graybeal, 2013).
- **Repair, rehabilitation and high-rise construction:** [AUTHOR INPUT REQUIRED: verified sources].

9.2 Sustainability considerations

UHPC contains much more cement per cubic meter than conventional concrete, so its per-volume embodied impact is high, but structural efficiency and durability may offset this at the structure level, which can only be shown through life-cycle assessment. Partial replacement of cement with supplementary cementitious materials and optimized packing has been investigated for reducing cement content (Yu et al., 2014; Yu et al., 2015), and a cost-effective optimization has been reported (Meng et al., 2017). Durability and potential service-life extension are widely cited advantages (Shi et al., 2015). Evidence at structure level is study-specific: in one recent cradle-to-grave analysis of twelve UHPC beams and four conventional concrete beams tested in bending, the UHPC beams showed life-cycle cost and carbon emission reductions of up to 55% and 58%, respectively, and omitting shear reinforcement lowered both further (Ghahsareh et al., 2025). These figures depend on that study's beam designs, monitoring data and maintenance assumptions and cannot be generalized. [AUTHOR INPUT REQUIRED: further verified life-cycle assessment studies.]

The advantages and limitations discussed in this review are summarized in Table 7.

Table 7. Advantages and limitations of UHPC.

Aspect	Advantages	Limitations/challenges
Mechanical strength	Very high compressive strength (over 200 MPa reported; Wille et al., 2011a) and tensile strength of about 7-14 MPa (Graybeal & Hartmann, 2003)	Testing is demanding because of machine capacity and end preparation, and specimen type affects results (Graybeal & Davis, 2008)
Durability	Durability properties reported to exceed HPC (Graybeal & Hartmann, 2003); no loss of mechanical properties after chloride exposure in one study (Abbas et al., 2015a)	Long-term in-service data are limited [AUTHOR INPUT REQUIRED: verified long-term studies]
Structural efficiency	Prestressed girder built without mild steel reinforcement (Graybeal, 2008)	Design assumptions can be conservative for lightly reinforced members (Russell & Graybeal, 2013); design provisions for some applications are lacking (Abbas et al., 2015b)
Crack control	Fibers bridge cracks and can give multiple fine cracks (Habel et al., 2006; Wille et al., 2014)	Post-cracking response is sensitive to fiber dispersion and orientation (Russell & Graybeal, 2013); fibers can reduce ductility of reinforced beams (Yoo & Yoon, 2015)
Construction	High flowability and near self-placing character reported for the FHWA-studied UHPC (Graybeal & Hartmann, 2003); rapid-strengthening formulations for field-cast connections (Graybeal & Stone, 2012)	Mixing and placing must be controlled to achieve fiber dispersion and orientation (Russell & Graybeal, 2013); strength gain depends on curing temperature (Graybeal & Stone, 2012)
Cost	Possible reduction in section size and maintenance (author interpretation; requires life-cycle analysis)	High binder and fiber content generally raise material cost (author interpretation) [AUTHOR INPUT REQUIRED: verified cost data]
Sustainability	Packing optimization and mineral admixtures can reduce cement content (Yu et al., 2015); durability may extend service life (Shi et al., 2015)	High cement content per unit volume; no verified life-cycle assessment is included [AUTHOR INPUT REQUIRED]

Applications	Bridge girders (Graybeal, 2008), field-cast connections (Graybeal & Stone, 2012), tunnel-lining segments (Abbas et al., 2015b)	Guidance exists (AFGC/SETRA, 2013; ACI Committee 239, 2018) but harmonization between documents is incomplete (author interpretation)
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Note. HPC = high-performance concrete; FHWA = Federal Highway Administration.

10. RESEARCH GAPS AND FUTURE DIRECTIONS

The following gaps follow from the evidence reviewed (author analysis):

1. Harmonized testing and reporting protocols for post-cracking flexure, including specimen size, notch use, toughness index and fiber orientation.
2. Quantitative links between casting-induced fiber orientation and flexural response, using validated orientation measurement.
3. Resolution of the conflicting evidence on the effect of fibers on compressive behavior and on the optimum fiber length, through factorial programmes with matched matrices and casting.
4. Size effects and loading-rate effects in compression and flexure, for which reliable data were not identified.
5. UHPC with high SCM content, local materials and alternative fibers, with full mechanical and durability characterization.
6. Life-cycle and cost assessment at structure level, and long-term durability data.
7. Constitutive models calibrated for design, including orientation, size and rate effects.
8. A systematic review of 2019-2026 literature, which this narrative review did not provide.

Table 8 summarizes existing knowledge, gaps and recommended research.

Table 8. Research gaps and future research directions.

Research area	Existing knowledge	Identified gap	Recommended future research
Compressive behavior	Conflicting reports on fiber effect (Abbas et al., 2015a; Lande & Thorstensen, 2021; Wei et al., 2021); cylinder and cube relations for 80-200 MPa UHPFRC (Graybeal & Davis, 2008); small geometry effect for fiber-free UHPC (Riedel et al., 2019); over 200 MPa without heat treatment (Wille et al., 2011a)	Conversion and size effects for fiber-reinforced UHPC; reliable compressive loading-rate data were not verified in this review	Inter-laboratory tests on fiber-reinforced specimens; rate-dependent compression tests
Flexural behavior	Girder behavior (Graybeal, 2008); fiber length effects (Yoo et al., 2016a); fiber orientation effects (Yoo et al., 2016b; Li et al., 2020; Maryamh et al., 2021); quasi-static and impact response (Yoo et al., 2018); tensile strain-rate response (Pyo et al., 2015)	Harmonized specimen size, test setup and orientation reporting	Beam tests with orientation mapping and standardized reporting
Fiber optimization	Conflicting length effects (Abbas et al., 2015a; Yoo et al., 2016a); hybrid fiber systems (Wei et al., 2021; Lande & Thorstensen, 2021; Li & Deng, 2021); strength-ductility trade-off in reinforced beams (Yoo & Yoon, 2015)	Systematic optimization of length, content, geometry and orientation	Factorial programmes with matched casting and orientation control
Sustainable UHPC	Cement reduction through packing and mineral admixtures (Yu et al., 2015); cradle-to-grave comparison of UHPC and conventional beams (Ghahsareh et al., 2025)	Validated life-cycle data and mechanical-durability trade-offs	Combined mechanical, durability and life-cycle studies

Long-term durability	No loss of mechanical properties after chloride exposure in one study (Abbas et al., 2015a); curing methods reviewed for compressive strength only (Hamada et al., 2022)	Long-term, fatigue and field-exposure data	Long-duration exposure and monitoring programmes
Numerical modeling	Finite element analysis with existing material models compared with flexural tests (Yoo et al., 2016a)	Constitutive models including orientation, size and rate effects	Calibrated and validated models for design

Research area	Existing knowledge	Identified gap	Recommended future research
Field applications	Girder (Graybeal, 2008), field-cast connections (Graybeal & Stone, 2012), tunnel-lining segments (Abbas et al., 2015b)	Design provisions and long-term performance monitoring	Instrumented field projects and design-oriented guidance

Note. UHPFRC = ultra-high performance fiber-reinforced concrete.

11. CONCLUSIONS

1. UHPC compressive strength is governed primarily by matrix packing, low water-to-binder ratio and curing; strengths of about 200 MPa or more are reported (Graybeal & Hartmann, 2003; Wille et al., 2011a), and no single curing regime is optimal for all materials (Hamada et al., 2022).
2. Evidence on whether fibers raise compressive strength is inconsistent between studies, and further matched comparisons are needed.
3. Flexural and post-cracking behavior are governed mainly by fiber content, geometry, orientation and bond, with higher fiber content giving stiffer post-cracking response and higher peak load over the ranges reviewed (Russell & Graybeal, 2013); fiber orientation can dominate the response.
4. Evidence on the best fiber length conflicts, and hybrid fiber systems are reported to be effective in two studies; differences are plausibly related to matrix, orientation, specimen size and test type.
5. Comparison across studies is limited by differences in specimens, test methods, toughness indices and reporting of orientation and curing.
6. This review is narrative, abstract-level and not systematic; its conclusions should be confirmed against full texts and extended with a systematic search before submission.

DECLARATIONS

Author contributions, funding, conflict of interest, data availability, acknowledgements and use of AI-assisted writing tools: [AUTHOR INPUT REQUIRED: complete according to the target journal's policy; disclosure of any AI-assisted drafting or editing is required by many journals and must be made accurately]. This review reports no original experimental data.

12. REFERENCES

(Citation style: author-year. † = DOI not verified; none is given rather than risk an incorrect one. ‡ = DOI taken from the reference list of Ullah et al. (2022) as displayed on PubMed Central; confirm at doi.org before submission. Sources with a DOI given without a mark were checked against an online record; most others were verified at abstract or record level only. See the accompanying reference-verification checklist.)

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