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Effect of Fibres on the Properties of Concrete.

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Abstract: Concrete is inherently brittle with low tensile strain capacity, leading to microcracking and sudden cataclysmic failure under overload. Fibre-reinforced concrete (FRC) mitigates these structural shortcomings through the introduction of discrete micro- and macro-fibres into the cementitious matrix. This paper presents a detailed critical review of ten representative case studies covering steel, polypropylene, synthetic, natural, bio-derived, and hybrid fibre systems. The synthesis demonstrates that while compressive strength exhibits variable or negligible gains depending on packing density and air entrainment, tensile strength, flexural toughness, postcracking residual capacity, and impact energy absorption are dramatically improved via crack-bridging and pull-out mechanisms. Key operational challenges including workability reduction, fibre balling, hydrophobic interface limitations, and matrix degradation are thoroughly evaluated alongside standardized testing protocols and durability implications.

Keywords: Fibre-reinforced concrete; Steel fibres; Polypropylene fibres; Natural fibres; Impact resistance; Post-cracking toughness; Flexural performance; Multi-scale crack bridging.

1. INTRODUCTION

Concrete remains the primary structural material worldwide owing to its low cost, local constituent availability, mouldability, and superior compressive performance.
However, conventional unreinforced concrete suffers from intrinsic brittleness, poor tensile strength, low impact resistance, and rapid crack propagation under service loads [1].
While macro-reinforcement bars provide structural capacity at the structural element scale, micro-level failure initiates within the hardened cement paste and aggregate interface. Dispersed
short discrete fibres bridge micro-cracks before they coalesce into macro-cracking, converting failure modes from brittle to quasi-ductile [2].
The structural mechanics of fibre inclusion rely on stress transfer across matrix discontinuities via mechanical anchorage, friction, and fibre pull-out dissipation [4]. This
review systematically analyzes ten distinct published research domains to assess material selection, mix design, mechanical response, dynamic impact resistance, and durability performance.

2. RESEARCH OBJECTIVES

This comprehensive critical review aims to fulfill four specific objectives across theoretical and applied structural domains:

- Synthesize structural findings from ten representative case studies covering metallic, synthetic, bio-based, and hybrid fibre systems.
- Investigate fundamental stress-transfer mechanisms including debonding, matrix anchoring, matrix friction, and energy dissipation.
- Evaluate practical trade-offs between workability, compressive strength, tensile capacity, impact energy absorption, and durability.
- Establish standard testing guidelines and highlight research gaps for prospective multi-performance concrete design.

3. REVIEW METHODOLOGY

A qualitative and analytical synthesis was conducted using indexed literature from peer-reviewed databases (Scopus, Web of Science). Studies were selected based on mechanistic clarity, experimental rigor, and practical relevance [5].

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4. FUNDAMENTAL MECHANISMS OF FIBRE REINFORCEMENT

4.1 Micro-crack Bridging and Stress Transfer

Before matrix cracking, fibres act as rigid inclusions with minimal load pickup due to high matrix stiffness relative to volumetric fraction. However, as micro-cracks initiate under applied strain, intersecting fibres carry tensile stresses across crack walls [2].

The efficiency of stress transfer depends on interface bond shear stress (τ_{bond}), aspect ratio (L/d), embedded length, and fibre modulus. Hooked ends or corrugated profiles enhance mechanical anchoring, preventing premature pull-out.

4.2 Post-Cracking Ductility and Strain Hardening

Unreinforced concrete loses load capacity immediately upon matrix cracking. In contrast, fibre-reinforced concrete (FRC) displays either strain-softening or pseudo strain-hardening behavior based on fibre volume fraction (V_f) and critical fiber content (V_{fcrit}) [4].

Strain-hardening FRC develops multiple fine micro-cracks across the gauge length, absorbing substantial mechanical energy before ultimate localization and failure occurs.

4.3 Compressive Behavior & Interfacial Voids

The influence of discrete fibres on uniaxial compressive strength is fundamentally limited and inconsistent across literature [5]. While micro-fibres restrict lateral expansion and micro-splitting, high volume fractions introduce air voids, poor compaction, and localized clumping.

Consequently, compressive strength may display slight increases (5–15%), remain unchanged, or decrease if mixing procedures fail to preserve fresh-state consolidation.

4.4 Energy Dissipation under Dynamic Loading

Dynamic impact and blast loading generate high strain rates (10^1 to 10^3 s^{-1}). Under shock waves, energy absorption occurs primarily through physical fibre pull-out and frictional sliding rather than matrix deformation [7].

Fibres prevent catastrophic spalling and structural fragmentation, maintaining structural integrity under impact shocks [8].

5. DETAILED ANALYSIS OF CASE STUDIES (PART I)

CASE STUDY 1: STEEL FIBRE-REINFORCED CONCRETE (SFRC) - STRUCTURAL & POST-CRACKING PERFORMANCE

Background & Mix Parameters: Steel fibres represent the most established structural reinforcement, characterized by high tensile strength ($E \approx 200\text{ GPa}$), high crack openings. Compressive strength shows modest gains ($>1000\text{ MPa}$), and deformed geometries (hooked-end, crimped, deformed length 30–60 mm) [2].

Performance Impact: Flexural strength and toughness increase by up to 100–200%, with significant residual load retention at elastic modulus (10–15%).

Practical Limitations: High self-weight, workability loss at $>1.0\%$ by volume, risk of fibre balling, and potential mechanical anchoring.

Mechanistic Findings: Hooked-end steel fibres provide dosages Upon crack initiation, plastic deformation of the end hooks generates substantial energy dissipation during pull-out [4].

surface corrosion under harsh marine exposure.

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CASE STUDY 2: POLYPROPYLENE MICROFIBRES - PLASTIC SHRINKAGE & EARLY-AGE CRACK MITIGATION

Background & Mix Parameters: Polypropylene (PP) **Performance Impact:** Plastic shrinkage cracking is reduced by microfibres are synthetic, lightweight (0.91 g/cm^3), up to 90%. Early-age bleeding and segregation are suppressed. chemically inert, and non-corrodible. Typically added at low Modest impact on ultimate hardened strength due to low dosages ($0.1–0.3\%$ by volume) [5]. modulus ($E \approx 3.5\text{ GPa}$).

Mechanistic Findings: Micro-fibres act during early plastic **Practical Limitations:** Hydrophobic surface limits chemical state (0–6 hours after casting) when tensile strain capacity is bond with C-S-H paste. Higher dosages severely reduce slump, extremely low. High surface area per unit volume provides fine requiring superplasticizer adjustments. bridging of capillary tension voids [6].

5. DETAILED ANALYSIS OF CASE STUDIES (PART II)

CASE STUDY 3: POLYPROPYLENE MACRO-FIBRES - DURABILITY & PERMEABILITY RESISTANCE

Background & Mix Parameters: Polypropylene macro-fibres **Performance Impact:** Enhanced freeze-thaw durability, (length 30–50 mm, embossed surface) are designed to provide reduced water permeability under head pressure, and superior structural residual flexural capacity without corrosion risks, resistance to chemical attack (sulphates, acids). serving as replacements for steel mesh in ground slabs [6].

Practical Limitations: Creep deformation under sustained

Mechanistic Findings: By restricting crack widths below 0.1 flexural loading; sensitive to fire exposure (melts at $\approx mm, macro-PP fibres limit continuous capillary paths, 160^\circ\text{C}$, though forming channels for steam relief). decreasing water sorptivity and
chloride ion ingress [5].

CASE STUDY 4: SYNTHETIC MACRO-FIBRE SYSTEMS (PVA, GLASS, BASALT)

Background & Mix Parameters: Advanced synthetic fibres **Performance Impact:** PVA enables Engineered Cementitious include Polyvinyl Alcohol (PVA), Alkali-Resistant Glass (AR- Composites (ECC) with strain capacity up to 3-5%. Basalt and Glass), and Basalt fibres, offering high tensile strength ($1000– glass enhance flexural strength significantly without weight 2500 MPa) [4]. additions.

Mechanistic Findings: PVA fibres form molecular hydrogen **Practical Limitations:** High cost; PVA interface can be overly bonds with hydration products, yielding strong chemical strong, causing fibre rupture rather than pull-out unless oiladhesion. AR-glass and basalt offer high stiffness for thin coated; glass/basalt vulnerable to long-term alkali attack if precast components. untreated.

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5. DETAILED ANALYSIS OF CASE STUDIES (PART III)

CASE STUDY 5: NATURAL FIBRE-REINFORCED CONCRETE (BIO-FIBRES)

Background & Mix Parameters: Natural vegetable fibres (sisal, jute, coir, bamboo, hemp) represent eco-friendly, low-cost housing applications. Typically added at 0.5–2.0% volume fraction [4].

Mechanistic Findings: Natural fibres provide crack bridging in environment over time (mineralization of cell walls); requires chemical treatments (alkali wash, silane coupling) to preserve and interfacial transition zone (ITZ) durability. quality.

Performance Impact: Improved impact absorption and post-cracking toughness for low-grade concrete elements. Reduces carbon alternatives. Typically added at 0.5–2.0% volume embodied carbon footprint. fraction [4].

Practical Limitations: Degradation in alkaline C-S-H affects matrix hydration

CASE STUDY 6: FIBRE-REINFORCED CONCRETE UNDER DYNAMIC IMPACT LOADING

Background & Mix Parameters: Evaluates drop-weight, split-Hopkinson pressure bar (SHPB), and projectile impact tests on SFRC and synthetic FRC [7][8].

Mechanistic Findings: Dynamic strain rates increase apparent material strength. Fibres arrest high-velocity crack propagation via multi-stage energy absorption.

Performance Impact: Drop-weight tests demonstrate up to 10 to 50-fold increases in initial cracking and ultimate failure energy. Prevents structural fragmentation.

Practical Limitations: Standardized test methods are lacking; dynamic numerical results across drop-weight and projectile setups cannot be directly compared without strain-rate calibration.

5. DETAILED ANALYSIS OF CASE STUDIES (PART IV)

CASE STUDY 7: GENERAL MECHANICAL PROPERTIES OPTIMIZATION & VOLUME FRACTION

Background & Mix Parameters: Broad experimental review of fibre volume fraction ($V_f = 0.2–2.0\%$), aspect ratio ($L/d = 50–100$), and matrix packing density [4].

Mechanistic Findings: Higher aspect ratios increase interfacial shear transfer, but beyond a critical aspect ratio (>80), fibre paste content; no universal dosage applies across all mixes. interlocking and balling severe degrade fresh mix homogeneity.

Performance Impact: Flexural strength reaches an optimum at specific dosage windows. Excessive fibre content increases entrapped air, resulting in declining compressive strength.

Practical Limitations: Optimum dosage must be experimentally tailored for every specific aggregate grading and mix homogeneity.

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CASE STUDY 8: HYBRID FIBRE SYSTEMS - MULTI-SCALE SYNERGY

Background & Mix Parameters: Synergistic combination of **Performance Impact:** Synergistic gains in first-crack strength, micro-fibres (e.g., PP or PVA, 0.1%) with stiff macro-fibres ultimate flexural capacity, and fracture energy, exceeding (e.g., hooked steel, 0.5–1.0%) [2][7]. additive predictions of single-fibre mixes.

Mechanistic Findings: Micro-fibres control micro-crack **Practical Limitations:** Complex mix design requiring initiation during early loading steps, while macro-fibres bridge specialized superplasticizers; high sensitivity to mixing order to wide macro-cracks under peak loading, yielding
multi-scale avoid segregation and clumping. protection.

5. DETAILED ANALYSIS OF CASE STUDIES (PART V)

CASE STUDY 9: FIBRE CONTENT, WORKABILITY & RHEOLOGICAL OPTIMIZATION

Background & Mix Parameters: Focuses on rheological **Performance Impact:** Requires high-range water reducers properties, slump flow, yield stress, and plastic viscosity of fresh (HRWR) and altered sand-to-aggregate ratios to ensure FRC under varying fibre dosages [5][6]. compaction without honeycombing.

Mechanistic Findings: Discrete fibres form a 3D internal **Practical Limitations:** Over-vibration during placement can skeleton that immobilizes free water and increases yield stress, cause heavy steel fibres to settle or synthetic fibres to float, drastically lowering slump. leading to anisotropic
property distribution.

CASE STUDY 10: TESTING METHODOLOGIES & STANDARDIZED EVIDENCE REQUIREMENTS

Background & Mix Parameters: Evaluates standard test **Performance Impact:** Establishes framework for minimum methods (ASTM C1609 flexural toughness, JSCE SF-4, EN testing requirements to substantiate performance claims in 14651 notched beam, drop-weight impact) [7][8][9]. commercial structural design.

Mechanistic Findings: Highlights that compressive **Practical Limitations:** Unmatched controls (varying w/c ratio cube/cylinder tests fail to capture fibre contribution; post-crack or paste content) lead to misleading claims in published flexural load-deflection response is essential. literature;
matched control mixes are mandatory.

6. COMPARATIVE PERFORMANCE MATRIX & RECOMMENDATIONS

Table 1. Comprehensive comparative matrix of fibre reinforcement strategies.

Fibre Type	Typical Dosage (V_f)	Primary Advantage	Compressive Effect	Flexural / Impact Effect	Main Technical Risk
Steel (Hooked)	0.5 – 1.5%	High toughness & residual load	Sloped gain (5–15%)	Substantial increase (>150%)	Corrosion, workability drop
PP Micro-fibre	0.05 – 0.2%	Plastic shrinkage control	Negligible / Unchanged	Minor flexural gain	Hydrophobic bond, slump loss
PP Macro-fibre	0.3 – 0.8%	Corrosion-free slab capacity	Unchanged / Sloped loss	Moderate post-crack gain	High flexural creep strain
PVA / Synthetic	0.5 – 2.0%	High ductility & crack width control	Moderate gain (10–20%)	Extreme ductility (ECC)	High cost, fibre rupture

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Natural (Sisal/Jute)	0.5 – 1.5%	Eco-friendly, low carbon footprint	Variable / Slight drop	Moderate early gain	Alkaline degradation over time
Hybrid Systems	0.5 – 1.5% total	Multi-scale crack control	Slight gain (5–10%)	Synergistic high performance	Rheology complexity

7. PRACTICAL RECOMMENDATIONS

Selection based on performance governing

- Criteria (shrinkage vs. impact vs. ductility).
- Utilize matched control mixes with identical water-binder ratio and paste
- volumes.

Gradual fibre addition to batching sequence to ensure uniform dispersion without clumping.

8. CONCLUSION

Discrete fibres convert brittle concrete into a tough, ductile composite through crack bridging and pull-out mechanisms. While compressive gains remain modest, flexural toughness, residual strength, and impact energy absorption display major enhancements. Hybrid systems provide optimal multi-scale crack protection.

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