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Research Article

Turning Industrial Waste into Strength: A Comprehensive Review of Fiber-Reinforced Concrete from Industrial Waste Materials

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Abstract:
This comprehensive review examines how industrial waste materials—specifically waste metallic fibres (WMF) and waste polypropylene fibres (WPF)—can be converted into high-performance concrete reinforcement. Waste fibres improve concrete behaviour by arresting crack propagation through pinching forces at crack tips, transforming brittle failure into a ductile, energy-absorbing response. Short fibres provide superior compressive strength; long fibres enhance flexural performance and post-cracking ductility; hybrid (multimodal) systems combining both yield optimal results. Waste polypropylene fibre-reinforced composites demonstrate post-cracking behaviour and load-carrying capacity that, in many cases, exceed waste metallic fibre performance despite lower density. Waste fibre-reinforced concrete (WFRC) reduces material costs by 20–40%, addresses waste management challenges, and delivers enhanced structural performance—transforming environmental liabilities into competitive advantages.

Keywords: Fibre-reinforced concrete, waste metal fibres, waste plastic fibres, sustainable construction, mechanical properties, circular economy, industrial waste valorisation

1 Introduction

Concrete: Strengths and Limitations

Concrete is humanity's most widely used manufactured material, valued for its durability, low cost, moldability, and compressive strength. Yet it exhibits poor tensile strength, limited ductility, and minimal energy absorption, causing catastrophic brittle fracture under tensile forces. Conventional reinforcement using steel rebars addresses tensile deficiencies but proves ineffective for crack control and is vulnerable to corrosion from moisture, chlorides, and carbonation—expanding corroded steel generates internal stresses that spall concrete cover, costing billions annually in infrastructure repairs. Modern fiber reinforcement distributes reinforcing elements throughout the entire concrete volume, controlling cracking at the micro-structural level. Fiber's arrest advancing cracks by applying pinching forces at crack tips, bridging crack faces and transforming concrete into a quasi-ductile composite capable of absorbing significant energy before failure.

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From Commercial to Waste Fibers

Commercial steel fibers command premium prices limiting widespread adoption, particularly in cost-sensitive applications. Industrial operations generate large quantities of metallic waste—machine shop shavings, lathe turnings, galvanized iron scraps—that can be used directly as concrete fibers without energy-intensive reprocessing. Similarly, polypropylene waste from packaging and automotive components offers a low-cost alternative to virgin PP fibers.

Tu and Kruger [1] presented "Oxyfluorination"—a novel surface modification treatment that significantly enhances interfacial bonding between fiber surfaces and concrete matrix, improving mechanical interlocking and chemical adhesion. Though currently experimental, such treatments could further optimize waste fibre performance in future WFRC applications.

Recycled Plastic Fibre Types

Four categories of recycled plastic fibers are used in concrete reinforcement:

- Virgin PP fibers (19 mm, slender): performance benchmark for waste alternatives
- Recycled melt-processed PP from automobile bumpers: 28 mm slender fibers with consistent geometry
- Automobile shredded residue: mixed PP and rubber, 18 mm flake form—low cost but variable
- Mixed plastic shredded waste: ~25 mm planar flakes from diverse plastic streams—maximises waste utilisation

Value Proposition of Waste Fibres

Category	Key Benefits
Economic	20–40% cost reduction vs. commercial fibres; converts disposal costs into raw material value
Environmental	Diverts industrial waste from landfills; reduces plastic pollution; lowers carbon footprint; supports circular economy
Technical	Effective crack control; improved ductility; enhanced energy absorption; reduced shrinkage and thermal cracking
Processing	Direct use without reprocessing; compatible with conventional mixing equipment

Nomenclature

Standard notation used throughout: "M20F30" designates M = Mix, 20 = compressive strength (MPa) at 28 days, F = fiber reinforcement, 30 = fiber length (mm).

II. RESEARCH FINDINGS: Comprehensive Property Analysis

A. Fresh Concrete Properties

1. Air Content

Bayasi and Zeng [4] conducted systematic experiments with waste fibrillated polypropylene fibers, creating seven mixture variations. Their findings revealed that air content increases proportionally with both fiber amount and length—pronounced when fiber volume exceeds 0.3%, while below this threshold air content equals or falls below control (fiber-free) levels. The rough, irregular surface texture of waste fibers enhances air bubble nucleation and stabilization.

Interestingly, Soroushian et al. [5] reported contrasting results, finding that recycled PP fiber addition actually reduces air content in concrete. This inconsistency suggests that waste fiber surface properties and processing history significantly influence air entrainment behavior.

Waste metallic fibers likely increase air content even more dramatically due to their highly crimped, irregular geometry. Fiber volume should be limited to approximately 3% to avoid adverse strength and density effects, unless air entrainment is deliberately sought for freeze-thaw resistance.

2. Workability

Bayasi and Zeng [4] performed slump and inverted slump cone tests (ASTM C 143-78 and ASTM C-995), demonstrating that inverted slump cone time increased with fiber addition—workability reduction becoming significant above 0.3% fiber volume. Fiber length proved critical: 19 mm fibers reduced workability far more dramatically than 12.7 mm fibers at equivalent volumes.

Soroushian et al. [5] investigated waste PP fiber effects, classifying them as macro fibers. They found that concrete viscosity increases due to fibers' large surface area and ability to absorb cement paste, creating a thicker, more viscous matrix resistant to flow.

Based on accumulated evidence, Mazaheripour et al. [9] recommend limiting fiber volume to 0.1–1% and incorporating superplasticiser admixtures to maintain adequate workability without increasing the water-cement ratio.

B. Hardened Concrete Properties

1. Compressive Strength

Mohammed Seddik Meddah and Mohamed Bencheikh [3] conducted comprehensive experiments comparing the effects of waste metallic and polypropylene fibre. Their systematic testing revealed that short fibers (<30 mm) decrease compressive strength while long fibers show minimal impact. Waste metallic fiber addition demonstrated negligible effects on compressive strength across length ranges tested.

Three mechanisms explain strength reductions from fiber addition: (i) increased porosity—fiber volumes create voids that cannot resist compression; (ii) aggregate disruption—incorporating fibers requires reducing coarse aggregate content, the primary strength contributor; (iii) fiber geometry variability—inconsistent waste fiber shapes create non-uniform stress distributions. WMFRC demonstrates better compressive performance than WPFRC primarily due to higher unit weight. Multimodal composites combining fibers of different lengths achieved the best compressive strength among fiber-reinforced formulations.

Beyond peak strength, Bayasi and Zeng [4] evaluated compressive toughness index (CTI) = (Energy absorbed to specified strain) / (Energy absorbed to peak stress). Their experiments revealed that long PP fibers (19 mm) reduce compressive strength but dramatically increase energy absorption capacity and toughness—exhibiting ductile rather than brittle response. Short fibers increase compressive strength when volume remains below 0.3%, after which strength gains plateau while toughness continues improving.

2. Flexural Behaviour

Mohammed Seddik Meddah and Mohamed Bencheikh's [3] experimental program revealed that adding either short or long waste metal or polypropylene fibers alone does not significantly improve flexural strength compared to control specimens (mono-fiber systems). However, combining both short and long fibers in multimodal systems dramatically enhances flexural strength—substantially outperforming control specimens and mono-fiber alternatives. Short fibers control crack initiation by bridging micro-cracks; long fibers arrest crack propagation by bridging macro-cracks and distributing stresses.

For WMFRC, ductility increases proportionally with fiber volume, though workability constraints limited testing to approximately 1% fiber volume. At equivalent fiber lengths and volumes, WPFRC yields superior flexural strength and ductility compared to WMFRC, likely due to polypropylene's superior elongation capacity enabling fibers to bridge cracks more effectively before rupturing.

Mono-fiber systems minimally affect post-cracking load retention. Multimodal systems produce superior post-cracking behavior: short fibers enhance crack initiation resistance while long fibers enable crack localization, creating quasi-ductile failure in WPFRC systems. S. Aravindan and C.D. Arunkumar [6] tested FRC formulations using industrial waste with M20 grade concrete, demonstrating approximately double the control beam flexural strength using 1% galvanized wire combined with 2% lathe scrap waste metallic fibers.

3. Durability

Brown et al. [13] investigated virgin PP fiber behavior by exposing fiber-reinforced concrete to salt water at temperatures ranging from -7°C to 70°C for six months. Results showed no reduction in tensile properties despite aggressive exposure, demonstrating PP's chemical stability in marine environments.

Won et al. [15] evaluated recycled PET fiber-reinforced concrete, finding excellent resistance to chloride salts ($CaCl_2$), superior resistance to sodium sulfate (Na_2SO_4), and maintained structural integrity in salt-contaminated environments.

Experiments by Ochi et al. [14] and ACI 544 [18] demonstrated that recycled PET fibers resist alkali attack effectively, maintaining properties in concrete's caustic pH 12–13 environment. Fraternali et al. [16] extended this research using PET fibers from post-consumer plastic bottles and measured 87% tensile strength retention after prolonged alkali exposure—confirming excellent alkali and sulfide resistance.

Silva et al. [18] conducted extended durability testing by immersing PET fiber specimens in Lawrence solution for 150 days at room temperature. This accelerated aging revealed surface degradation of fibers and corresponding toughness reduction—indicating that while PET resists short-term chemical attack, long-term exposure gradually degrades performance, suggesting fiber surface protection may be necessary for critical long-term applications.

Soroushian et al. [5] evaluated abrasion resistance following ASTM C779 protocols, finding that most discrete fiber reinforcement systems exhibited reduced abrasion resistance compared to plain concrete—due to fibers near the surface debonding during abrasion and creating voids. Surface treatments or protective coatings are recommended for high-abrasion applications.

4. Toughness and Impact Resistance

Mohammed Seddik Meddah and Mohamed Bencheikh [3] measured toughness as the area under load-displacement curves. Their toughness index calculations revealed that WPF provided substantially greater toughness than WMF. Polypropylene's higher elongation capacity before rupture enables more energy absorption through fiber stretching and pull-out. Waste metallic fibers' random orientation and irregular geometry create stress concentrations that reduce energy absorption efficiency.

Bayasi and Zeng [4] found that impact resistance improves more dramatically with short fiber addition than long fibers, provided fiber volume doesn't adversely affect workability. Soroushian [5] demonstrated substantial impact resistance increases for discrete (randomly distributed) reinforcement systems—the random three-dimensional fiber network creates tortuous crack paths that dissipate energy more effectively. Aravindan [6] recorded a 23.7% improvement in impact resistance for waste fiber-reinforced concrete compared to control specimens in falling weight impact tests.

III. Synthesis and Design Recommendations

Fresh Concrete Guidelines

Parameter	Guideline
Air Content	Limit fiber volume to ~3% to avoid adverse air content effects. Exploit air entrainment only when freeze-thaw resistance is a design objective.
Workability	Prefer short fibers for workability-sensitive applications. Add superplasticiser when fibre volume exceeds 0.5%. Consider spray-suction dewatering for high fibre volumes. Limit fibre length when conventional placement methods are required.

Hardened Concrete Design Guidelines

Objective	Fiber Recommendation	Volume Target
Maximum compressive strength	Short (<30 mm), slender metallic fibres	<0.3%
Maximum toughness / energy absorption	Long (≥30 mm) PP fibres	0.5–1.0%
Superior flexural strength + ductility	Multimodal: short + long fibres combined	0.5–1.5%
Best impact resistance	Short PP or metallic fibres	<0.5%
Balanced overall performance	Hybrid metallic + PP, multimodal lengths	0.75–1.5%

Unit weight significantly affects compressive strength—WMFRC outperforms WPFRC in compression due to higher density, with experiments demonstrating up to 41.25% compressive strength increase when waste metallic fibers replace polypropylene alternatives. Slender fibers perform better than non-slender alternatives by creating fewer voids.

Economic and Sustainability Considerations

Factor	Details
Waste metallic fibre cost	60–80% less expensive than commercial steel fibres
Waste polypropylene cost	70–90% less expensive than virgin PP fibres
Overall, concrete cost reduction	20–40% depending on fibre volume
Environmental benefits	Diverts thousands of tons from landfills annually; eliminates energy-intensive reprocessing; reduces virgin material demand; qualifies for LEED and BREEAM certifications

Implementation Barriers

1. Fibre Quality Variability: Waste sources produce inconsistent fibre geometry, requiring quality control protocols
2. Industry Conservatism: Construction sector resistance to novel materials and approaches
3. Design Code Limitations: Current codes lack provisions for waste fibre-reinforced concrete design
4. Performance Certification: Absence of standardised testing and acceptance criteria
5. Supply Chain Development: Need for reliable waste collection and processing infrastructure

IV. Future Research Directions and Conclusions

Critical Knowledge Gaps

While existing research establishes WFRC feasibility, several areas require further investigation:

1. Design Fundamentals: New analytical models are needed for waste fibres' variable configurations, crimped and irregular shapes, macro-fibre behaviour, and metal versus plastic mechanical property differences.
2. Long-Term Performance: Multi-decade durability data under field conditions including freeze-thaw cycling, sustained chemical exposure, fibre-matrix bond degradation, carbonation, and chloride penetration resistance.
3. Optimization Algorithms: Machine learning approaches to identify ideal fiber length distributions, volume fractions, aspect ratios, and hybrid system compositions for specific applications.
4. Standardisation and Codification: Standardized testing protocols for waste fibre characterisation; quality control specifications; design code provisions; performance-based specifications rather than prescriptive requirements.

Key Technical Conclusions

1. Waste fibers effectively control cracking through crack-tip pinching mechanisms that delay propagation
2. Short fibers optimize compressive strength when volumes remain below 0.3%
3. Long fibers enhance ductility and toughness despite modest strength reductions
4. Multimodal fiber systems deliver superior overall performance by combining complementary mechanisms
5. Polypropylene waste fibers provide better post-cracking behavior than metallic alternatives in many scenarios

6. Durability generally equals or exceeds conventional concrete in most exposure conditions

Realizing WFRC's full potential requires collaborative efforts among researchers, industry, code bodies, policymakers, and practitioners. The technical foundation established through decades of research proves that waste fiber-reinforced concrete represents not merely an acceptable alternative but potentially a superior choice for many applications. WFRC simultaneously addresses waste management, resource conservation, cost reduction, and carbon footprint reduction—a rare solution delivering benefits across all dimensions of sustainable construction.

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