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Research Article

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Posted Date: September 23rd, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10964542/v1>

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Additional Declarations: No competing interests reported.

INFLUENCE OF RECYCLED WASTE PET FIBER GEOMETRY ON THE DESTRUCTIVE, NON-DESTRUCTIVE, AND POST-FAILURE CHARACTERISTICS OF STRUCTURAL CONCRETE

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Abstract

This experimental study investigates the performance of M20 structural concrete incorporating discrete fibers recovered from post-consumer Polyethylene Terephthalate (PET) beverage bottles. Straight (ST) and corrugated zigzag (ZZ) fibers with an aspect ratio of 40 were introduced into concrete mixtures at a 1% volumetric replacement of coarse aggregate. Specimens were cured under open-air field weathering conditions for 28 days to evaluate environmental exposure effects. Fiber addition reduced workability, lowering slump by 9.62% for ST mixes and 32.69% for ZZ mixes due to increased specific surface area and mechanical interlocking. Destructive compressive strength testing revealed minor strength reductions relative to the plain concrete control (20.20 MPa), achieving 18.90 MPa for ST and 17.65 MPa for ZZ mixes. Non-destructive Schmidt rebound hammer testing systematically underestimated the actual core compressive strength by 43.97% and 54.20% in the fiber-reinforced mixes, as the low-modulus polymer fibers dampened the surface impact energy. Consequently, empirical calibration factors were established to correct non-destructive rebound estimates against destructive test results ($f_{c,destructive} = 1.785 \times f_{c,rebound}$ for ST; $f_{c,destructive} = 2.179 \times f_{c,rebound}$ for ZZ). While control specimens exhibited brittle shear failure and straight fibers showed pullout debonding, the zigzag profile provided superior mechanical anchorage within the cementitious matrix, effectively suppressing lateral spalling and enhancing post-peak ductility.

Keywords: Recycled PET; Fiber-reinforced concrete; Fiber geometry; Mechanical interlock; Field curing; Schmidt rebound hammer.

Acknowledgment

We would like to express our sincere appreciation to the Engineering Materials Laboratory of Lovely Professional University, Punjab for their invaluable support and assistance in conducting the test.

Author Contribution

Rukaya Yasmin wrote the main manuscript, while Kundan Yadav collected the required data and information. All authors reviewed the manuscript.

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1 Introduction

1.1 Background and Development of Concrete Technology

Concrete is the most common and widely used construction material globally. Derived from the Latin term *concretus* meaning "to grow together" concrete is a composite material formed by coarse granular aggregate (filler) embedded in a hard binding matrix of cement paste that fills voids and adheres the particles together (Jiang et al., 2022). The basic composition can be defined as:

$$\text{Concrete} = \text{filler} + \text{binder}$$

Depending on the binder used, concrete is classified into non-hydraulic cement, hydraulic cement, asphalt, or polymer concrete. Non-hydraulic and hydraulic cements both require water to mix and react, but hydraulic cement possesses the capacity to gain strength submerged in water (Khan, 2022; Sabari & Noh, 2024).

Table 1: Advantages and Limitations of Concrete

ADVANTAGES AND LIMITATIONS OF CONCRETE	
ADVANTAGES	LIMITATIONS
1. Economical and energy-efficient	1. Low tensile strength (~10% f_c)
2. Ambient temperature curing	2. Low ductility and brittleness
3. Formability into complex shapes	3. Volume instability
4. Fire, water, and heat resistance	4. Low strength-to-weight ratio
5. Ability to consume waste products	5. Rapid microcrack propagation

Plain concrete exhibits a very low tensile strength typically only one-tenth of its compressive strength alongside low ductility and little resistance to cracking (Ali Mahamoud Ghlaio et al., 2024). Internal microcracks are naturally present within the concrete paste, and their unchecked propagation under loading leads to brittle fracture (Christopher et al., 2023). Advancements in concrete technology have yielded high-performance solutions, including lightweight concrete, high-strength concrete, self-consolidating flowing concrete, polymer concrete, and Fiber-Reinforced Concrete (FRC).

1.2 Principles and Characteristics of Fiber-Reinforced Concrete (FRC)

Fiber-Reinforced Concrete is a composite material consisting of hydraulic cement, fine and coarse aggregates, water, and discontinuous, discrete, uniformly dispersed fibers. Continuous meshes, woven fabrics, and long rebar wires are excluded from this classification. Adding small, closely spaced fibers creates an internal crack-arresting mechanism that improves flexural performance, enhances impact resistance, and alters the failure mode of the concrete matrix (Aljalawi, 2005; Balaji & Srinivasarao, 2026; Salim & Salim, 2024).

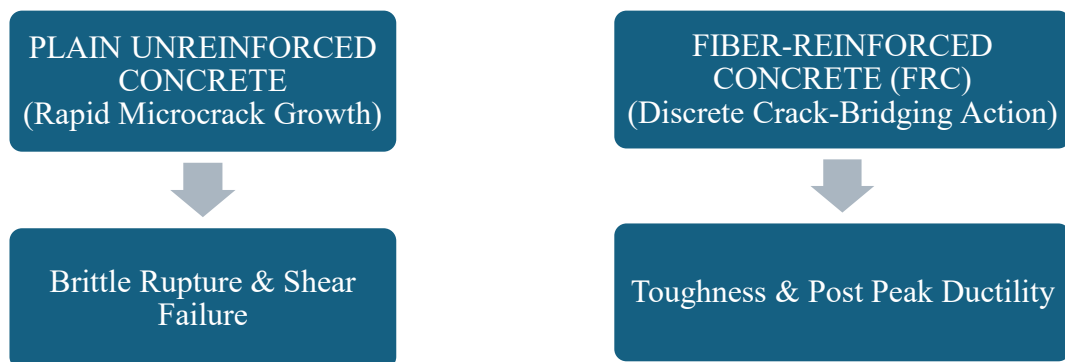


Figure 1: Plain Unreinforced Concrete Vs Fiber-Reinforced Concrete

The efficiency of fiber reinforcement depends on several geometric and material parameters:

- **Aspect Ratio (L/D):** The ratio of fiber length (L) to its equivalent diameter (D), commonly ranging between 30 and 150. Short (discontinuous) fibers maintain aspect ratios between 20 and 60, whereas long (continuous) fibers range from 200 to 500.
- **Volume Fraction (V_f):** Conventional applications utilize low fiber volumes (e.g., 0.4% to 2% for steel fibers and 0.06% to 0.5% for synthetic polymeric fibers). High-Performance FRCs (HPFRC) such as SIFCON (5%-20% steel fibers), SIMCON (6% steel fiber mats), and Compacted Reinforced Composites (5%-10% fine steel fibers) exhibit strain-hardening behaviors with tensile strain capacities reaching 1.5%.
- **Material Types:** Steel, glass, natural organic/mineral fibers (asbestos, wood, bamboo), polypropylene (PP), nylon, Kevlar, and polyester.

Table 2: Influence of Fibers on Mechanical Behavior

INFLUENCE OF FIBERS ON MECHANICAL BEHAVIOR	
PROPERTY	OBSERVED INFLUENCE / ENHANCEMENT
1. Compressive Strength	Minor change (0 to 15% variation)
2. Modulus of Elasticity	Slight gain (~3% increase per 1% V_f)
3. Flexural Strength	Up to 2.5x increase with 4% fiber dosage
4. Fracture Toughness	10 to 40 times higher than plain concrete
5. Splitting Tensile	Up to 2.5x increase with 3% fiber dosage
6. Impact Resistance	5 to 10 times that of unreinforced concrete
7. Shrinkage & Permeability	Controls plastic/drying cracking & bleeding

1.3 Prior Investigations on Recycled PET in Concrete

Extensive experimental research has evaluated the mechanical and material behaviors of recycled polyethylene terephthalate (PET) incorporated into cementitious composites across various replacement strategies and fiber configurations. In aggregate replacement applications, utilizing waste plastic as a sand substitute reduces raw material costs while mitigating solid waste disposal burdens (Ismail & AL-Hashmi, 2008). Low-volume substitutions such as replacing 5% by weight of natural sand with unwashed waste PET aggregates maintain comparable workability and enhance post-peak ductility, albeit with slight reductions in compressive and splitting tensile strengths (Frigione, 2010). At higher replacement volumes, synthetic lightweight aggregates fabricated from PET bottles and granulated blast-furnace slag (GBFS) have been shown to increase mix workability by 123%, though accompanied by a 33% reduction in 28-day compressive strength at a 75% replacement ratio (Choi et al., 2005), a trend further corroborated by regional investigations on recycled plastic coarse aggregates (Hasan et al., 2015).

Beyond aggregate replacement, the incorporation of PET as discrete fiber reinforcement significantly enhances composite toughness and cracking resistance. Discrete domestic plastic fibers can yield measurable improvements in compressive strength (Ramalingam & Murugesan, 2011), while post-consumer bottle fibers (10–20 mm in length at 0.05%–0.30% volume fractions) substantially improve 28-day flexural toughness and impact resistance without adversely affecting compressive capacity (Pelisser et al., 2012). Furthermore, straight fibers cut directly from waste PET bottles enhance overall structural ductility and demonstrate favorable interfacial adherence with the cement matrix (Foti, 2011). The efficacy of these mechanisms is closely tied to physical dimensions; fiber aspect ratio, length, and surface profiling play a decisive role in maximizing crack-bridging performance and mitigating plastic shrinkage cracking (Banthia & Gupta, 2006; Hussain & Yadav, 2023; Soroushian et al., 1993).

Long-term composite durability remains governed by the chemical stability of the fiber–matrix interface. Untreated PET fibers are susceptible to alkaline hydrolysis within the high-pH pore solutions of Portland cement, which can lead to progressive surface deterioration under prolonged alkaline curing; however, the application of protective surface coatings effectively preserves composite integrity, and exposure to sulfate environments induces minimal degradation (da Silva Neto et al., 2025; Deshbhratar et al., 2024; Wiliński et al., 2016).

1.4 Problem Statement and Research Objectives

Despite the advantages of recycled PET fibers, standard straight plastic strips possess smooth surfaces that limit mechanical bonding and interlock with the surrounding concrete matrix. Straight fibers are susceptible to pullout under stress rather than fully transferring tensile forces across fracture planes. Profiling PET fibers into a zigzag geometry introduces mechanical anchorage within the hardened matrix, functioning similarly to deformed rebar configurations.

Furthermore, while standardized laboratory evaluations rely on controlled indoor curing tanks, in-situ structural concrete is routinely cured under ambient field weathering conditions where rain overflow, fluctuating solar radiation, and variable temperatures directly influence hydration. In addition, evaluating fiber-reinforced concrete using non-destructive testing (NDT) requires verified correlation models with destructive cylinder testing (DT).

Table 3: Experimental Program Outline of Concrete Mix

EXPERIMENTAL PROGRAM OUTLINE	
1. Concrete Design Class	M20 Grade (1:2:3 Mix Ratio)
2. Water-Cement Ratio (w/c)	0.53
3. Fiber Replacement Level	1% by volume of Coarse Aggregate
4. Evaluated Fiber Geometries	Straight (ST) & Zigzag (ZZ)
5. Fiber Dimensions	Length = 40 mm, Aspect Ratio = 40
6. Curing Conditions	28-day open-air field weathering
7. Testing Standards	ASTM C143, ASTM C39, ASTM C805

1. To establish a practical method for converting locally collected post-consumer waste PET bottles (Coca-Cola and Sprite containers) into straight and deformed zigzag discrete fibers.
2. To investigate the effects of straight and zigzag PET fibers on the fresh workability (slump) of M20 concrete.
3. To evaluate and compare the 28-day destructive compressive strength (f'_c) of plain concrete, straight PET fiber concrete, and zigzag PET fiber concrete cured under field weathering conditions.
4. To measure non-destructive surface hardness using a Schmidt Rebound Hammer (NDT) and formulate empirical correlation equations connecting NDT results to destructive crushing strengths.
5. To evaluate the failure modes, post-cracking coherence, cracking patterns, and interlocking mechanisms of straight versus zigzag PET fibers.

2 Materials and Experimental Methods

2.1 Raw Material Properties

The experimental investigation utilized hydraulic cement, natural river sand (fine aggregate), crushed stone (coarse aggregate), potable drinking water, and recycled waste plastic bottle fibers.

- **Cement:** Ordinary Portland Cement (OPC) conforming to ASTM C150/C150M (Type I) was sourced locally from Phagwara, India. The cement comprises approximately 95% clinker and 5% gypsum, with no major supplementary cementitious additions. Standard consistency (ASTM C187) and Vicat needle setting times (ASTM C191) were determined experimentally (ASTM International, 2016, 2021c, 2022).
- **Fine Aggregate:** Natural river sand was collected from the campus of Lovely Professional University (LPU), Punjab. To eliminate foreign particles and oversized debris, the sand was passed through a standard No. 4 sieve (4.75 mm opening) in accordance with ASTM C33 (ASTM International, 2018a). Fine aggregates were prepared in a Saturated Surface Dry (SSD) condition by laboratory air drying to

prevent moisture loss and stored in airtight containers. Physical indices including Fineness Modulus (FM), specific gravity, absorption capacity (ASTM C127/C128), and rodded unit weights (ASTM International, 2015a, 2015b, 2017) were established.

- **Coarse Aggregate:** Crushed stone aggregate with a 20 mm maximum aggregate size (downgraded) was selected. The stones were sieved to satisfy standard grading distributions according to ASTM C33, washed thoroughly to remove adhering rock dust, and conditioned to an SSD state prior to batching. Bulk/apparent specific gravity, water absorption capacity, rodded bulk density, and void fractions were measured per ASTM C29 and ASTM C127 (ASTM International, 2017, 2018a).
- **Mixing Water:** Normal potable tap water free from visible impurities, suspended solids, and foaming agents was used for concrete batching and curing.

Table 4: Properties of Coarse Aggregate, Fine Aggregate and Cement.

Material Property	Coarse Aggregate	Fine Aggregate	Cement
Fineness Modulus (FM)	6.520	2.663	—
Bulk Specific Gravity (OD)	2.511	2.140	—
Bulk Specific Gravity (SSD)	2.615	2.260	—
Apparent Specific Gravity	2.639	2.485	—
Absorption Capacity (%)	0.840	6.387	—
Unit Weight (Oven-Dry) (kg/m ³)	1540	1603.67	1440 (approx.)
Unit Weight (SSD) (kg/m ³)	1554.10	1715.55	—
Void Content (%)	40.33	25.13	—
Initial Setting Time (min)	—	—	105
Final Setting Time (min)	—	—	235
Normal Consistency (%)	—	—	29.85

2.2 Fabrication and Geometric Profiling of Recycled PET Fibers

Post-consumer waste Polyethylene Terephthalate (PET) beverage bottles (carbonated soft drink containers) were gathered from the LPU university. The fabrication of straight and deformed zigzag fibers was carried out through the following systematic procedure:

RECYCLED PET FIBER FABRICATION PROCESS

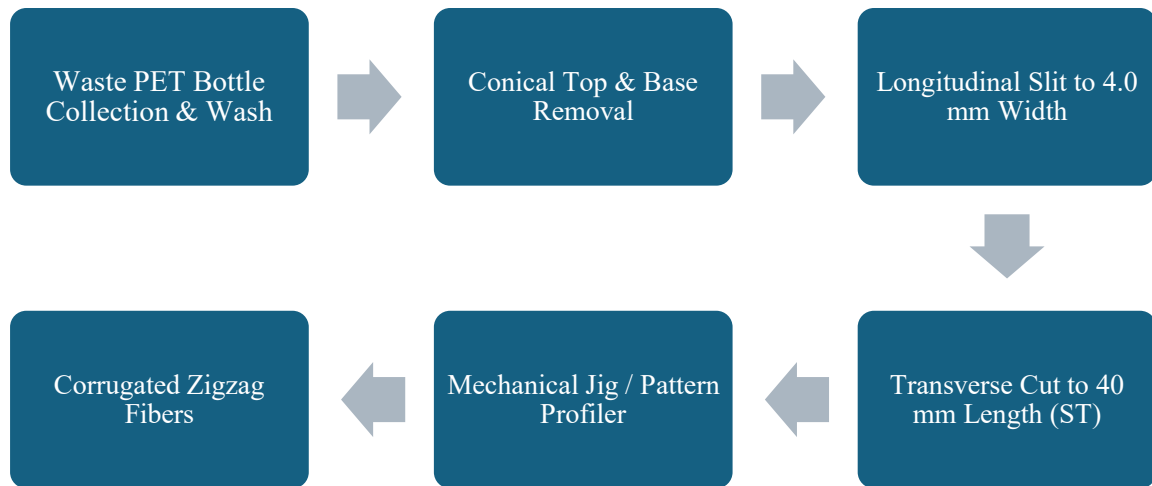


Figure 2: Recycled Pet Fiber Fabrication Process

1. **Sectioning:** The conical neck portion and the irregular bottom base of each bottle were excised using cutting shears.
2. **Longitudinal Slitting:** The remaining smooth cylindrical middle wall was mounted onto a mechanical guide and slit into uniform strips measuring 4.0 mm in width and 0.2 mm in sheet thickness.
3. **Length Sizing (Straight Fibers):** The strips were cut into discrete 40 mm lengths using a calibrated cutting ruler, producing straight PET fibers (ST) with an equivalent diameter (D) of 1.0 mm and an aspect ratio (L/D) of 40.
4. **Deformation Profiling (Zigzag Fibers):** Straight strips were passed through a manual zigzag gear profiling device to introduce continuous corrugations prior to cutting into equivalent 40 mm profiled segments (ZZ), maintaining an identical aspect ratio (L/D=40) to emulate deformed reinforcing elements.

Table 5: Property Parameter of Straight PET Fiber and Zigzag PET Fiber

Fiber Property Parameter	Straight PET Fiber (ST)	Zigzag PET Fiber (ZZ)
Nominal Length, L (mm)	40	40
Strip Width, W (mm)	4.0	4.0
Strip Thickness, T (mm)	0.2	0.2
Equivalent Diameter, D (mm)	1.0	1.0
Aspect Ratio (L/D)	40	40
Density (kg/m ³)	1355	1355
Profile Geometry	Linear, smooth surface	Corrugated, interlocking profile



Figure 3: Preparation of Zigzag PET fibers and Straight PET fibers

2.3 Mix Proportions and Design Matrix

Concrete mixture proportions were established in accordance with ACI 211.1-91 targeting an M20 grade concrete composite. A nominal binder-to-aggregate mass ratio of 1:2:3 was used with a fixed water-cement ratio (w/c) of 0.53 and a design air content allowance of 2.0%.

To evaluate the influence of geometric profiling, three distinct cases were formulated:

- **Control Concrete (0% PF):** Plain reference concrete without fiber additions.
- **Straight Fiber Concrete (1% ST PF):** Composite with 1% of coarse aggregate volume replaced by straight PET fibers.
- **Zigzag Fiber Concrete (1% ZZ PF):** Composite with 1% of coarse aggregate volume replaced by corrugated zigzag PET fibers.

The absolute mass of PET fiber replacement (M_f) was derived from the displaced coarse aggregate solid volume ($V_{CA,rep}$) and the density of PET ($\rho_{PET} = 1355 \text{ kg/m}^3$):

$$V_{CA,rep} = 0.0075 \times \left(\frac{M_{stone}}{\rho_{stone}} \right)$$

$$M_f = V_{CA,rep} \times \rho_{PET} = 7.92 \text{ kg/m}^3$$

Table 6: Concrete Mixture Proportions

Mix Designation	Fiber Type	Coarse Agg. Replacement (% Vol.)	Cement (kg/m ³)	Fine Agg. (kg/m ³)	Coarse Agg. (kg/m ³)	Water (kg/m ³)	PET Fibers (kg/m ³)
0% PF (Plain)	None	0.00	300.00	600.00	900.00	159.00	0.00
1% ST PF	Straight	1.00	300.00	600.00	892.08	159.00	7.92
1% ZZ PF	Zigzag	1.00	300.00	600.00	892.08	159.00	7.92

2.4 Mixing, Casting, and Environmental Weathering Curing

Mixing was carried out on a non-absorbent, water-tight steel platform using a multi-stage dry-to-wet blending sequence to prevent fiber balling and ensure uniform dispersion:

Table 7: Concrete Batching and Casting Sequence

CONCRETE BATCHING & CASTING SEQUENCE
1. Uniformly spread weighed fine aggregates across the steel platform. 2. Distribute Portland Composite Cement over the sand bed. 3. Hand-trowel the sand-cement phase until reaching a uniform color. 4. Evenly scatter discrete PET fibers (ST or ZZ) across the dry matrix. 5. Add coarse aggregate; dry-mix three times from perimeter to center. 6. Create a central crater; introduce 75% of batch water and mix. 7. Add remaining 25% water incrementally while blending to consistency.

- Molding and Compaction:** Fresh concrete was cast into standard cylindrical molds measuring 4 inch in diameter by 8 inch in height. Inner mold surfaces were coated with mineral grease to facilitate demolding. Filling was executed in three equal layers, each consolidated with 25 strokes of a standard 16 mm (5/8 in) hemispherical-tipped tamping rod in accordance with ASTM C31 (ASTM International, 2021a). Specimen tops were leveled and troweled smooth. A total of six sets of cylindrical specimens were prepared across the mix variations.
- Field Curing Regime:** Following 24 hours of ambient setting, the specimens were demolded and submerged within open-air water containers at the Engineering Materials Laboratory, LPU. The curing setup remained exposed to outdoor weathering conditions for 28 days. The specimens were subjected to natural environmental variables including ambient sunlight fluctuations, rain runoff and overflow, and dissolved organic exposure.

2.5 Testing Procedures and Evaluation Standards

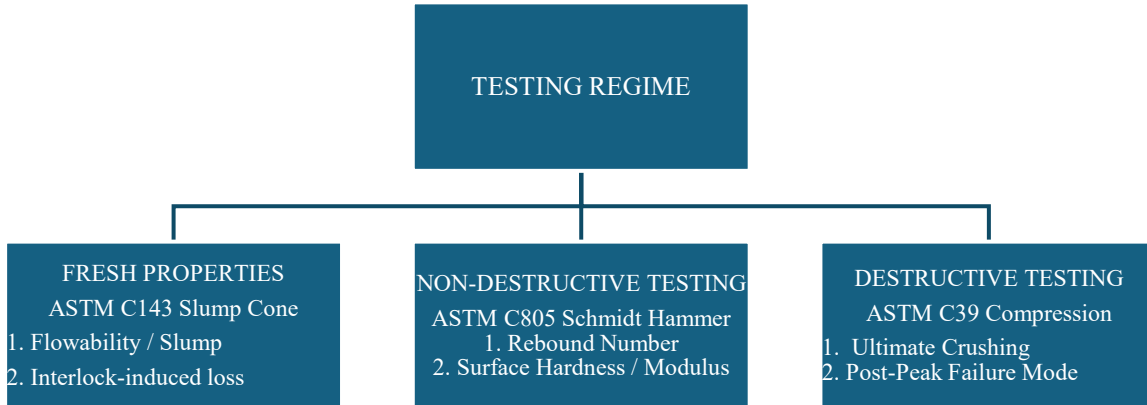


Figure 4: Testing Procedures and Evaluation Standards

2.5.1 Workability Measurement (ASTM C143)

Fresh consistency and rheological behavior were assessed immediately after mixing using a standard slump cone (12-inch height, 4-inch top diameter). The mold was filled in three layers, rodded 25 times per layer with a 16 mm (5/8 in) diameter rod (mass ~930 g), and vertically lifted to determine the slump subsidence in inches (ASTM International, 2020).

2.5.2 Destructive Compressive Strength Testing (ASTM C39)

Hardened compressive strength (f'_c) was evaluated at 28 days of curing using an automated hydraulic testing machine with a capacity of 1500 kN. Specimens were positioned axially between loading platens equipped with elastomeric capping pads to ensure uniform stress distribution across the bearing surfaces. A constant axial loading rate of 0.15 MPa/s was applied until complete material fracture. The ultimate crushing strength was calculated as:

$$f'_c = \frac{P_{\max}}{A_c}$$

Where $P_{\max}$ is the peak axial failure load and A_c is the cross-sectional area of the 4 in by 8 in concrete cylinder.

2.5.3 Non-Destructive Rebound Hammer Testing (ASTM C805)

Prior to destructive crushing, non-destructive surface hardness was measured on the dry cylinder surfaces using a Type-N Schmidt Rebound Hammer. The hammer plunger was oriented perpendicular to the smooth specimen surface. Ten individual rebound readings separated by minimum 1-inch intervals were recorded per specimen. The mean rebound index was converted into equivalent non-destructive compressive strength using standard calibration charts, enabling direct correlation with the destructive testing values. Failure interfaces, crack patterns, lateral spalling, and fiber anchorage mechanisms were visually recorded post-test (ASTM International, 2018b).

3 Results and Discussion

3.1 Fresh Concrete Behavior and Workability Loss

The workability of fresh concrete mixes was evaluated via standard slump measurements in accordance with ASTM C143. The addition of recycled PET bottle fibers caused a measurable reduction in slump values across all modified mixes. The control mix (0% PF) achieved a baseline slump of 5.2 inches. The inclusion of 1% straight PET fibers (1% ST PF) reduced the slump to 4.7 inches, representing a 9.62% loss in workability. The mixture

containing 1% zigzag PET fibers (1% ZZ PF) exhibited a more pronounced drop, yielding a slump of 3.5 inches, corresponding to a 32.69% reduction compared to the control.

Table 8: Workability Comparison (Slump Value)

Concrete Mix	Fiber Dosage (% Coarse Agg. Replacement Vol.)	Slump Value (in)	Workability Reduction (%)
0% PF (Control)	0.00	5.2	Reference (0.0%)
1% ST PF	1.00	4.7	9.62%
1% ZZ PF	1.00	3.5	32.69%

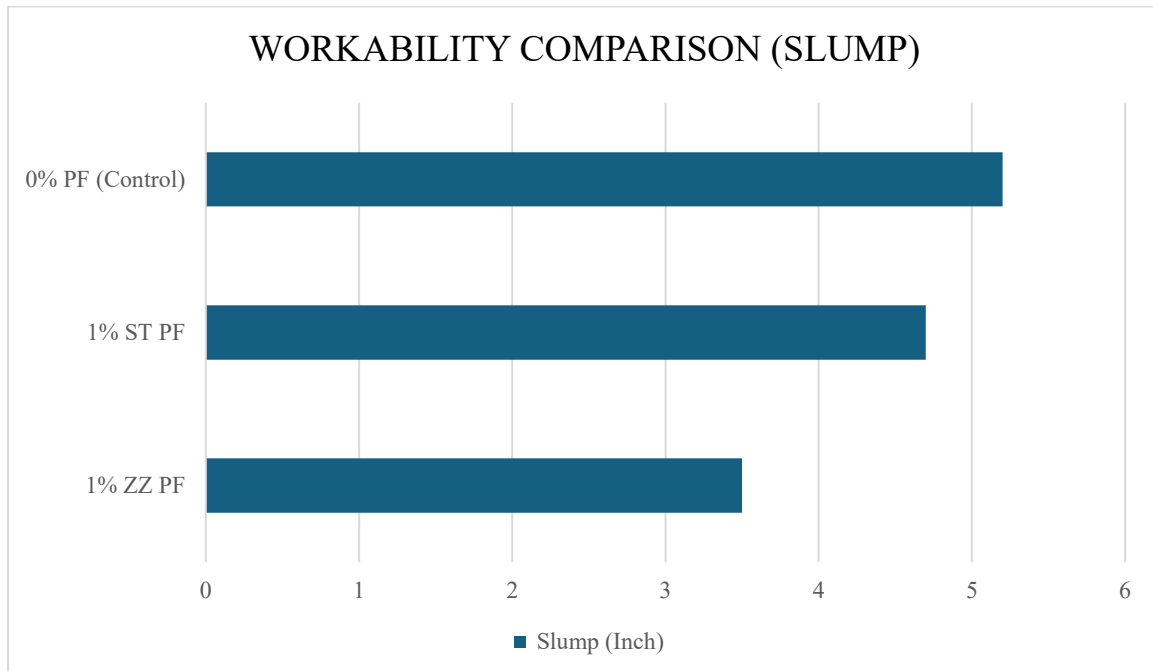


Figure 5: Bar graph for Workability Comparison

The reduction in slump when incorporating discrete PET fibers is primarily attributed to the increased surface area of the inclusion phase, which demands a higher volume of cement-sand paste for adequate particle lubrication. In the case of zigzag fibers, the corrugated geometric profile enhances physical entanglement and internal mechanical interlocking among aggregates and mortar constituents, restricting the free gravitational flow of the fresh mixture.

3.2 Destructive Compressive Strength (f'_c) Performance

The 28-day destructive compressive strength was determined using a universal compression testing machine (ASTM International, 2021b). The control concrete reached an ultimate compressive strength of 20.20 MPa. The inclusion of 1% straight PET fibers resulted in a marginal strength decline to 18.90 MPa, reflecting a negligible reduction of 6.4%. The zigzag PET fiber mix (1% ZZ PF) developed an average compressive strength of 17.65 MPa, corresponding to a 12.6% reduction relative to the control specimen and 6.2% lower than the straight fiber



Figure 1: Bar graph for Destructive Compressive Strength Comparison

composite.

The observed reductions in compressive strength can be explained by several microstructural mechanisms:

- **Interfacial Transition Zone (ITZ) Weakness:** The smooth, non-polar hydrophobic surfaces of recycled PET strips yield lower chemical and adhesive bonding with the hydrophilic Portland cement paste compared to natural mineral aggregates.
- **Entrained Micro-Voids:** The manual incorporation of corrugated zigzag profiles introduces localized micro-cavities within the compacted matrix, slightly increasing internal porosity.
- **Field Curing Environment:** Specimen exposure to outdoor weathering including direct solar thermal cycles, rainfall overflows, and organic deposition varied hydration rates relative to standard temperature-controlled laboratory curing tanks.

Despite these factors, the destructive compressive capacity remained close to target M20 design specifications, confirming that low volumetric fractions (1%) of recycled PET fibers can be incorporated without compromising structural load-carrying capacity.

3.3 Non-Destructive Testing (NDT) Evaluation and Empirical Correlation

Non-destructive surface hardness tests conducted via Schmidt Rebound Hammer (ASTM C805) systematically yielded lower compressive strength estimations compared to direct crushing methods across all specimens.

Table 9: Destructive Vs Non-destructive Strength Comparison

Concrete Mix	Destructive Strength, DT (MPa)	Non-Destructive Strength, NDT (MPa)	Ratio (DT/NDT)	Strength Discrepancy (%)
0% PF (Control)	20.20	14.90	1.356	-26.24%
1% ST PF	18.90	10.59	1.785	-43.97%

1% ZZ PF	17.65	8.10	2.179	-54.20%
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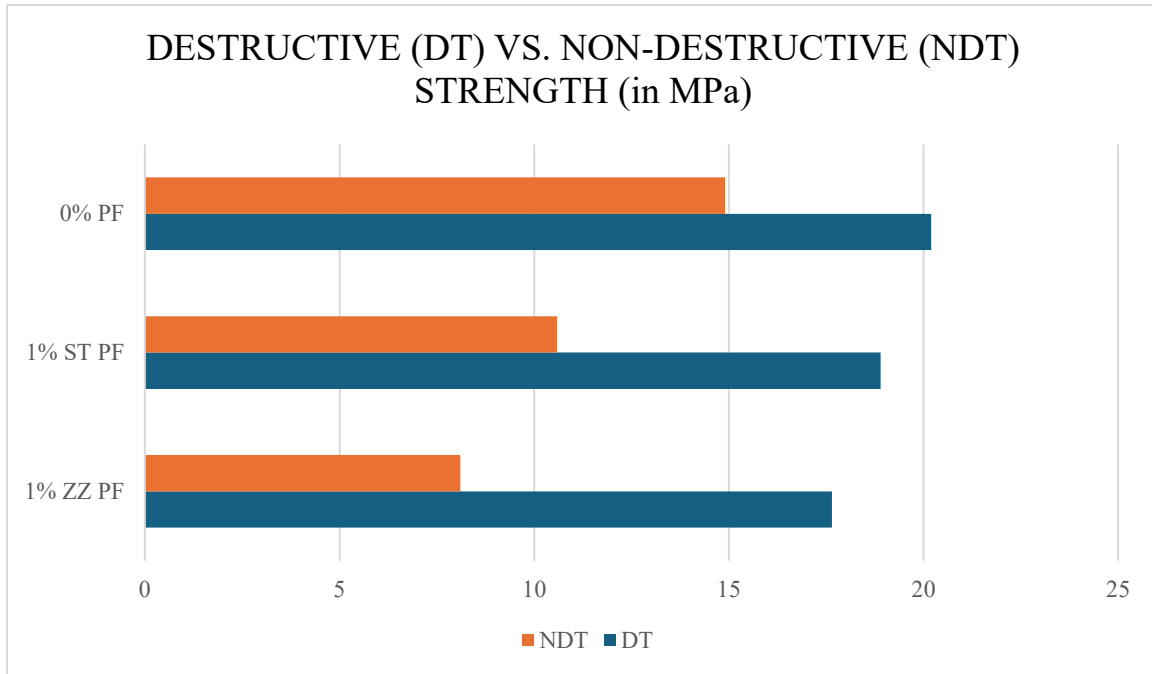


Figure 7: Bar graph for Comparison of Destructive and Non-destructive Strength

The lower values obtained from rebound hammer testing are attributed to surface-layer mechanics. While destructive tests measure the composite core capacity of the cylinder, rebound testing evaluates localized surface hardness and elastic restitution. Polymer fibers distributed near the specimen perimeter dampen the mechanical impact energy of the hammer plunger due to their lower modulus of elasticity compared to rock aggregates. Consequently, zigzag fibers which retain more paste around their corrugated profiles exhibit higher elastic damping, reducing the rebound index.

To account for this damping effect, empirical conversion models were established to correlate non-destructive rebound data directly to the actual crushing strength:

Plain Concrete (0% PF): $DT = 1.356 \times NDT$

Straight PET Fiber Concrete (1% ST PF): $DT = 1.785 \times NDT$

Zigzag PET Fiber Concrete (1% ZZ PF): $2.179 \times NDT$

These conversion models provide practical calibration equations for in-situ non-destructive quality evaluation of recycled PET fiber-reinforced concrete structures.

3.4 Failure Mechanisms, Crack Propagation, and Post-Peak Behavior

Visual and structural inspection of cylinders following compressive failure demonstrated distinct differences in failure modes, crack patterns, and post-peak structural coherence.

Table 10: Failure Mechanism Characteristics of Different Mix Concrete

FAILURE MECHANISM CHARACTERISTICS			
PARAMETER	PLAIN CONCRETE	STRAIGHT FIBER	ZIGZAG FIBER
• Primary Failure Mode • Post-Peak Cohesion • Cracking Density • Lateral Spalling • Dominant Fiber Role	• Brittle shear fracture • None (Complete break) • Very low (Single cone) • Severe fragmentation • N/A	• Axial splitting • Moderate • High (Splitting) • High • Friction/Pullout	• Axial splitting • High (Anchored) • Moderate (Arrest) • Low / Restrained • Mechanical Lock

- **Plain Concrete (0% PF):** Failed in a typical brittle shear fracture mode. The absence of internal crack arrestors resulted in sudden diagonal shear cone formation accompanied by complete matrix fragmentation and immediate loss of load capacity.
- **Straight Fiber Concrete (1% ST PF):** Exhibited a transition from shear fracture to axial splitting. The randomly dispersed straight fibers intersected longitudinal tensile cracks, bridging opening planes. However, due to smooth surface interfaces, straight fibers experienced pullout debonding at higher strains, resulting in visible crack widening and partial spalling of the outer concrete shell.
- **Zigzag Fiber Concrete (1% ZZ PF):** Demonstrated the highest level of post-peak integrity and ductile crack containment. While failing via axial splitting, the specimen preserved its cylindrical geometry without severe spalling or crumbling. The continuous geometric corrugations of the zigzag profile generated mechanical interlock within the surrounding mortar, analogous to ribbed steel rebar. This mechanical anchorage anchored the fibers against premature pullout, redistributing tensile stresses, controlling crack opening widths, and improving composite toughness and ductility.

4 Conclusions and Recommendations

4.1 Conclusions

An experimental investigation was conducted to evaluate the influence of recycled Polyethylene Terephthalate (PET) bottle fibers on the fresh, destructive, non-destructive, and post-cracking mechanical behaviors of M20 structural concrete under open-air field weathering conditions. Based on the experimental findings, the following conclusions are drawn:

- **Workability and Rheology:** The incorporation of recycled PET fibers reduces the workability of fresh concrete. Mixes containing straight fibers experienced a 9.62% slump reduction, whereas zigzag fibers led to a 32.69% reduction compared to plain concrete. The corrugated geometry of zigzag fibers introduces physical entanglement that holds the cement-sand paste, increasing internal flow resistance.
- **Destructive Compressive Strength:** The addition of 1% PET fibers by volume of coarse aggregate resulted in minor compressive strength reductions. Straight PET fiber concrete exhibited a minimal decrease of 6.4% (18.90 MPa vs. 20.20 MPa for control), while zigzag fiber concrete decreased by 12.6% (17.65 MPa). These results verify that low volumetric fractions of recycled PET fibers preserve the baseline compressive load capacity of standard structural mixes.
- **Non-Destructive Testing (NDT) Sensitivity:** Compressive strength evaluated via the Schmidt Rebound Hammer systematically underestimated actual crushing values due to near-surface elastic damping caused by the low-modulus polymer fibers. Compared to plain concrete (14.90 MPa), the straight and zigzag fiber concrete recorded surface strength drops of 28.90% (10.59 MPa) and 45.63% (8.10 MPa), respectively. Empirical calibration factors ($DT=1.785 \times NDT$ for straight; $DT=2.179 \times NDT$ for zigzag) were developed to enable reliable in-situ rebound evaluations.

- **Failure Modes and Mechanical Interlock:** Fiber inclusion altered the failure mechanism from sudden, brittle diagonal shear fracture in plain concrete to ductile axial splitting. Straight fibers experienced pullout debonding, causing visible surface spalling. In contrast, zigzag fibers provided mechanical anchorage within the cement paste analogous to deformed reinforcing rebars, effectively suppressing matrix disintegration, controlling crack propagation, and improving post-peak composite toughness.
- **Field Curing Influence:** Exposure to ambient environmental weathering (natural sunlight cycles, rainfall dilution/overflow, and organic matter deposition) influenced the hydration rate and strength-gaining performance of the concrete specimens over the 28-day curing period.

4.2 Limitations of the Study

- **Source Material Specificity:** The discrete fibers were fabricated manually from locally sourced post-consumer beverage bottles (Coca-Cola and Sprite soft drink containers), which may exhibit minor variations in wall thickness and polymer grade.
- **Curing Variability:** Field curing relies on local ambient weathering conditions, which vary across geographical locations, seasons, and microclimates.
- **Single Fiber Dosage:** The investigation was limited to a single volumetric replacement ratio of 1% and one nominal mix proportion (M20, 1:2:3, w/c= 0.53).

4.3 Recommendations for Future Research

- **Dosage Optimization:** Future research should evaluate a broader spectrum of fiber volume fractions to determine the optimum replacement threshold for balancing workability and toughness.
- **Mix Designs and Binders:** The effects of different design mix proportions, varying water-cement ratios, and the incorporation of chemical admixtures (such as superplasticizers or viscosity modifiers) should be investigated to recover workability losses.
- **Geometric Variations:** Studies should explore varying fiber lengths, aspect ratios (L/D), and alternative corrugated profiles to optimize the interfacial bond and load-transfer efficiency.
- **Structural Member Performance:** Large-scale structural testing should be conducted on reinforced concrete elements incorporating zigzag PET fibers, including flexural beams, beam-column joints, elevated slabs, and staircases.
- **Numerical and Analytical Modeling:** Finite element analysis (FEA) and constitutive modeling should be developed to formulate standardized structural design guidelines for recycled PET fiber-reinforced composites.

Declarations

Ethics Approval: Not applicable. This study does not involve human participants, human data, or animal experimentation.

Consent to Participate: Not applicable.

Consent to Publish: Not applicable.

Clinical Trial Registration: Not applicable. This research does not involve clinical trials or human health interventions.

Competing Interests: The authors affirm that they have no known competing financial interests or personal relationships that could have influenced the work reported in this manuscript.

Funding: This research received no external funding.

Availability of Data and Materials: The datasets generated and analyzed during the current study are included within this published article.

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