An Examination of the Mechanical Performance of Eco-Friendly Concrete Incorporating Recycled PET and Tire Steel Fibers

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ABSTRACT

The increasing demand for sustainable construction has prompted investigations into the use of recycled materials in concrete production. This research examines the mechanical performance of eco-friendly concrete reinforced with fibers derived from post-consumer waste, including Polyethylene Terephthalate (PET) fibers from plastic bottles and recovered steel fibers from scrap tires. Polypropylene (PP) fibers and industrial micro straight steel fibers were used for comparison to evaluate the performance of recycled fibers. The research aimed to assess the viability of recycled Fiber-Reinforced Concrete (FRC) as a sustainable alternative that reduces waste and conserves natural resources. Experimental mixes were designed with two fiber volume fractions of 0.5% and 1%, for both recycled and industrial fibers. Standardized procedures were utilized for testing fresh properties (workability) and mechanical properties (compressive strength, splitting tensile strength, and flexural strength). Relative to the reference mix (normal concrete), the results revealed that the use of recycled fibers significantly improved most mechanical properties. Tire steel fibers at 1% volume fraction achieved the highest improvements, with a 42% increase in compressive strength and 77% increase in splitting tensile strength, outperforming recycled PET fibers by 22.6% and 19.4%, respectively. Additionally, incorporating tire steel fibers at a 1% volume fraction improved flexural strength by 43.8%. Recycled PET fibers and PP fibers augmented compressive and splitting tensile strengths but reduced flexural strength by 27% and 18.8%, respectively. The results indicated that recycled fibers could efficiently reinforce concrete and provide an eco-friendly alternative to conventional fibers. By reducing environmental impact, decreasing reliance on natural resources, and diverting waste from landfills, these approaches encourage sustainable construction.

Keywords-eco-friendly concrete; recycled tire steel fibers; recycled polyethylene terephthalate fibers; fiber-reinforced concrete; fiber volume fraction

I. INTRODUCTION

Concrete is a composite material which has been used in construction applications, such as foundations, bridges, walls, roads, dams, reservoirs, and architectural structures, but is brittle in nature. To improve its properties, multiple methods have been explored, one of which is the integration of fibers [1, 2]. Recycled waste fibers promote environmental sustainability while enhancing mechanical properties and durability. This method not only improves toughness and shrinkage control but also reduces environmental impact by efficiently utilizing waste materials [3-6]. The need for concrete and to conserve natural resources positions eco-friendly FRC as a viable alternative for the future of construction.

The use of PP fibers recovered from waste packaging, and steel fibers from discarded tires has been examined. Authors in [7] studied foamed concrete beams reinforced with plastic fibers under flexural loading using experimental methods and ABAQUS finite element analysis. The numerical and experimental results were very similar, with only 5–8% variation in the ultimate load and the maximum deflection being 3–7% lower in the analysis results. The parametric study showed that increasing the primary reinforcement area made the ultimate load capacity higher and the deflection lower than in the control specimen. Authors in [8] investigated shear failure in RC beams by incorporating recycled PET fibers and Carbon Fiber Reinforced Polymer (CFRP) shear reinforcement. Fourteen shear-critical beams were cast with PET fiber volumes from 0.25–1.5%; half used steel stirrups and half carbon CFRP strips. At 1% fiber, shear strength increased by 11.45% (CFRP) and 8.45% (stirrups). Incorporating fiber up to 1.25% resulted in an 8.61% improvement in shear ductility for CFRP and a 9.96% enhancement for stirrups, hence augmenting durability and sustainability in structural applications. Roller compacted concrete augmented with PP fibers has also been studied, analyzing its strength and durability characteristics [9]. The results indicated that increasing fiber content diminished compressive strength, unit weight, and overall durability, but enhanced water absorption. Despite these disadvantages, PP fibers exhibited commendable resilience to freeze-thaw cycles, suggesting possible advantages in some durability-focused applications. Another environmentally sustainable high-strength lightweight concrete was developed by including nanosilica as a partial substitute for cement, utilizing waste glass powder as aggregate, and integrating recycled PP fibers [10]. Glass powder (20–30%), nanosilica (1–3%), and fibers (0.5–1.5%) were combined with LECA lightweight aggregate. The ideal composition, containing 1.5% fibers, 3% nanosilica, and 25% glass, achieved around 1.7 times higher compressive strength and 1.6 times higher tensile strength, while reducing CO_2 emissions by almost 3%.

Adding Recycled Steel Fibers (RSFs) extracted from tires as concrete reinforcement has been investigated, contrasting their performance with Industrial Steel Fibers (ISFs) [11]. The research findings indicated that RSFs bonded effectively with the concrete matrix, showing good pull-out performance. Moreover, adding fibers (either RSFs or ISFs) did not significantly change compressive strength, indicating no adverse impact on basic concrete strength. Finally, RSF-reinforced concrete displayed excellent toughness and energy absorption, comparable to or slightly below ISF-reinforced mixes. The utilization of steel bead wires, repurposed from scrap tire beads, has also been tested as fiber reinforcement in Self-Compacting Concrete (SCC) [12]. The objective was to assess the impact of varying fiber contents (1–5% by concrete weight) on the characteristics of both fresh and hardened concrete. The main findings indicated that the ideal fiber dosage is roughly 4% by weight, beyond which the advantages decrease. Steel bead wires significantly increased flexural strength by up to six times. Short-term salt exposure did not substantially impact the strength of fiber-reinforced concrete. At higher fiber contents, careful mix adjustments were required, where workability issues emerged. In addition, authors in [13] examined alkali-activated slag-based SIFCON supplemented with continuous steel fibers sourced from scrap tires and activated with NaOH in conjunction with either sodium silicate or finely ground waste glass. Thirty combinations with up to 5% fibers attained compressive values above 100 MPa and flexural strengths surpassing 75 MPa, demonstrating that waste-based composites can be equal or surpass traditional concretes while promoting sustainability. Authors in [14] examined Recycled Polyethylene Terephthalate (R-PET) fibers, with promising results in enhancing post-cracking behavior and reducing shrinkage [14]. PET bottles constitute roughly 11% of landfill content and due to the chemicals used in their manufacture, improper use, and disposal they have serious environmental consequences [14]. PET-based concretes can mitigate CO_2 emissions, address plastic waste disposal issues, and reduce global pollution [15]. Authors in [16] investigated the impact of integrating R-PET fibers from post-consumer bottles into Portland limestone cement concrete, focusing on long-term seawater curing. The results indicated that R-PET fibers did not diminish compressive strength and, in fact, slightly enhanced it during air curing. Seawater exposure, however, reduced flexural toughness, decreased energy absorption and ductility, thereby showing limited appropriateness for marine conditions. Optimal performance was attained at a fiber concentration of 1.0% by volume, which improved splitting tensile strength, crack mitigation, ductility, and shear resistance. Elevated fiber content (>1%) diminished workability and overall quality. These results were also confirmed in [17]. Finally, PET with enhanced surfaces has been tested as a replacement for fine aggregate in concrete production [18]. The PET particles were treated by coating them with Silica Fume (SF) or cement and exposing them to microwave heating for a set duration. Concrete specimens were produced with PET at volume ratios of 10%, 15%, and 20%, and their mechanical performance was evaluated. The findings revealed that this technique significantly enhanced concrete quality, with increased compressive strength and reduced water absorption. The results may contribute to more efficient and sustainable construction practices.

Reinforced concrete with recycled fibers enables enhancing structural performance and addressesing environmental concerns by reducing waste and carbon footprint. In this context, the current study aims to assess, contrast, and rank the multicriteria-based performance of a total of eight formulations of mixtures prepared with volume fractions (V_f) of 0.5% and 1% of recycled waste scrap tires, R-PET, micro straight steel fiber, and PP fiber in addition to the reference normal concrete, focusing on their influence on mechanical properties. The study contributes to the body of knowledge on sustainable construction materials and seeks to provide practical insights for engineering applications.

II. EXPERIMENTAL PROGRAM

A. Material Properties

1) Concrete

Resistant Portland cement, manufactured by AL-JESR/Lafarge cement factory [19], with a specific gravity of 3.15, was used in all mixes. The physical and chemical properties of cement are illustrated in Table I [16]. Natural sand was used as fine aggregate with a specific gravity of 2.62. Crushed coarse aggregate with a maximum particle size of 19 mm and a specific gravity of 2.67 was also utilized, meeting the requirements of [20]. The particle size distribution values for fine and coarse aggregates are illustrated in Figures 1 and 2. Mixing water was used with a water/cement (w/c) ratio of 0.32 [21]. A third-generation polycarboxylate-based high-range water-reducing and set-retarding superplasticizer was used at dosages of 1% and 0.8% of cement weight (within the proposed range of 0.5–2.0%), as indicated in the data sheet of the manufacturer [22], to increase workability. All mixture components are outlined in Table II.

TABLE I. PHYSICAL PROPERTIES AND CHEMICAL COMPOSITION OF CEMENT

Physical properties				
Fineness (m^2 /Kg)	**Initial setting time (min)**	**Final setting time (min)**	**Compressive strength (MPa)**	
			2 days	**28 days**
291	66	240	17	32
Chemical composition				
Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3
%(weight)	61	21	5	4
Oxide	MgO	SO_3	L.O.I	I.R
%(weight)	3.5	2.3	2.3	0.6

TABLE II. RAW MATERIALS USED IN THE MIXTURE DESIGN

	Cement kg/m^3	**Sand kg/m^3**	**Gravel kg/m^3**	**Water kg/m^3**	**Superplasticizer % of cement**
Normal concrete	380	800	1010	122	0.8
Fiber concrete	380	800	1010	122	1

a. Water cement ratio (w/c =0.32) kg/m^3

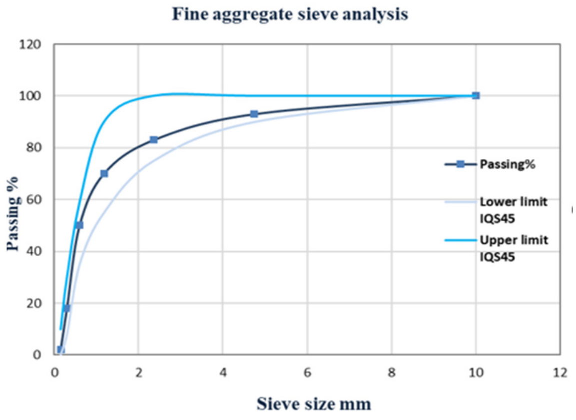


Fig. 1. Fine aggregate grading size distribution [20].

2) *Recycled Fibers*

Two types of recycled fiber were used in this study, in percentages of 0.5% and 1%. The details of the fibers, based on literature, are shown in Table III. The first type was PET fiber (E) that is used in the production of soft drink bottles. The waste bottles were collected from the environment, cleaned, cut, and the middle part was shredded, using a paper shredder machine, into rectangular shape pieces measuring 30 mm in length, 4 mm in width, and 0.32 mm in thickness. The dimensions were determined by the paper shredding machine output, as depicted in Figure 3. The second type of recycled fiber is scrap tire fiber (T) brought from Diwaniyah tire factory. These fibers are made by shredding the scrap tires, and subsequently isolating and separating the steel fibers, which vary geometrically. They were then cleaned and the bigger pieces were isolated, as illustrated in Figure 4. The length and diameter of the remaining quantity ranged between 4-45mm and 0.09-0.5mm, respectively, as portrayed in Figure 5. This high variability is a result of the mechanical recycling process.

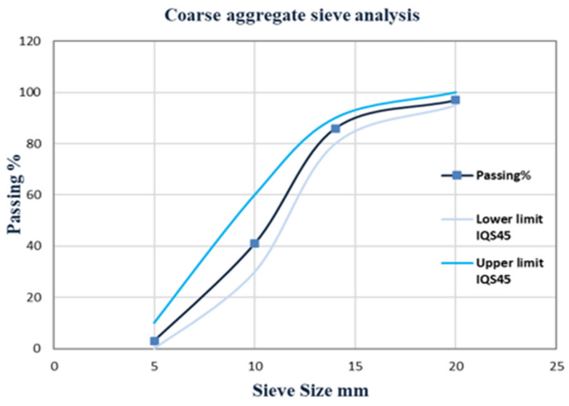


Fig. 2. Coarse aggregate grading size distribution [20].

TABLE III. RECYCLED PET FIBER AND SCRAP TIRE FIBER PROPERTIES BY MANUFACTURE

	PET fiber	**Tire fiber**
Dimeter (D), mm	4	0.09-0.5
Average length (L), mm	32	4-45
Aspect ratio (L/D)	8	44-90
Tensile strength, MPa	200	2010
Elastic modulus, GPa	3	200
Density, kg/m^3	1300	7850
Color	Crystalline white	Dark gray to black

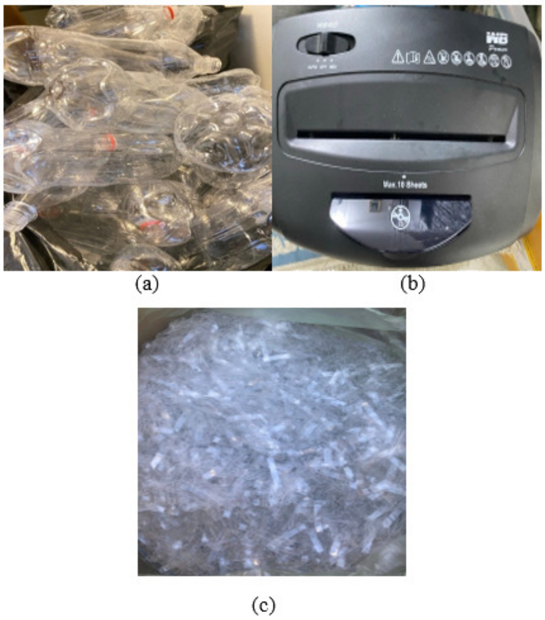
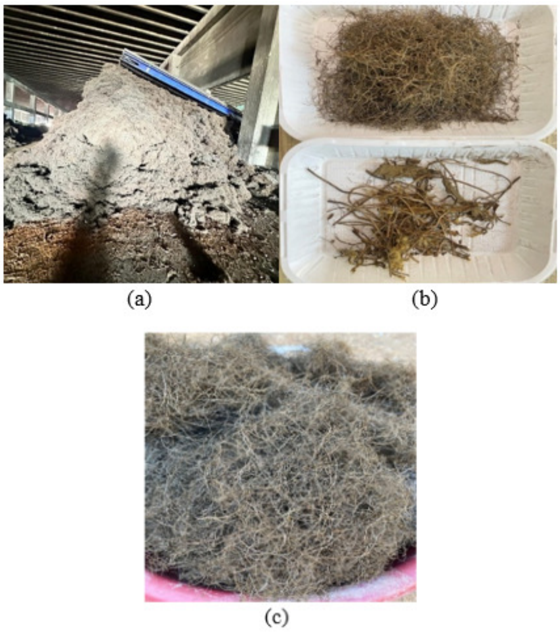
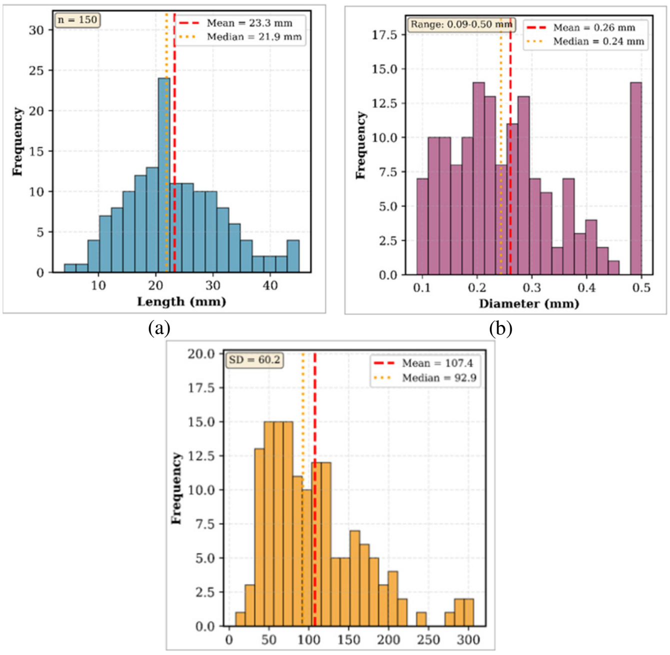


Fig. 3. R-PET fiber preparation stages: (a) waste bottle collection, (b) paper shredder machine, (c) recycled fiber.


(a) (b)

(c)

Fig. 4. Recycled waste scrap tire fiber preparation stages: (a) waste scrap tires, (b) cleaning of unwanted parts, (c) recycled fiber.



(a) (b)

(c)

Fig. 5. Distribution characteristics of recycled tire steel fibers: (a) length distribution, (b) diameter distribution, (c) aspect ratio distribution.

3) *Industrial Fibers*

PP fiber (P) and micro straight steel fiber (S), as illustrated in Figure 6, with V_f values of 0.5% and 1% were used for comparison with the recycled fibers. The factory specification details of the fibers are summarized in Table IV.


(a) (b)

Fig. 6. Industrial fibers: (a) PP, (b) micro straight steel fiber.

TABLE IV. PP FIBER AND MICRO STRIGHT STEEL FIBER DETAILS

	PP fiber	**Micro straight steel fiber**
Dimeter (D) mm	0.018	0.2
Average length (L) mm	12	13
Aspect ratio (L/D)	667	65
Tensile strength MPa	400	2850
Elastic modulus GPa	4	200
Density kg/m^3	910	7800
Color	White	Gold

B. *Characteristics and Casting of the Specimens*

A total of four fiber-reinforced mixtures and a normal concrete mixture for reference were made, as detailed in Table V. Three types of specimens for each V_f value were cast, cured, and tested, as depicted in Figure 7, to investigate their basic mechanical properties. The specimen’s cross-sectional dimensions were 100×100×100 mm cubes, 100 mm diameter, and 200 mm height cylindrical molds, and 100×100×400 mm prisms. The casting process began with mold preparation by cleaning and oiling, followed by precise weighing of the materials. Mixing was performed in a 0.5 m³ horizontal rotary mixer, where sand and gravel were first blended, then cement, and finally water and superplasticizer to form a homogeneous mixture. For FRC, fibers were added gradually and mixed for an additional 1 min. No significant balling was observed. The fresh mix was placed in three layers into the molds, each compacted using a vibration rod, then nylon sheets were used to cover it and prevent moisture loss for 24 h. Subsequently, specimens were cured for 28 days in a water tank at 20 ± 2°C until testing.

TABLE V. DETAILS AND DESIGNATION OF THE MIXTURES

No	**Mixture name**	**V_f**	**Designation name**
1	Normal concrete	0	N
2	Micro straight steel fiber	1	S1
3		0.5	S0.5
4	Waste scrap tire fiber	1	T1
5		0.5	T0.5
6	PP fiber	1	P1
7		0.5	P0.5
8	PET fiber	1	E1
9		0.5	E0.5

Fig. 7. Casting of concrete mixtures.

III. RESULTS AND DISCUSSION

This section presents the results from the assessed outcomes for fresh concrete (slump test) and hardened concrete (compressive strength test, splitting tensile strength test, and flexural strength test).

A. Fresh Concrete

In compliance with [23], the workability was evaluated using the slump test, as displayed in Figure 8. The inclusion of fibers, particularly at higher V_f, generally reduced slump values. Plastic fibers caused a moderate reduction due to fiber entanglement and surface area effects, whereas steel fibers had a more pronounced impact on slump because of their rigidity and potential for interlocking, which impedes workability. The slump test results for normal concrete were recorded as 11cm and decreased with the addition of fibers to the FRC mixture. This reduction is attributed to the increased particle content, which restricts the mobility of the cement particles and increases mixture viscosity. The continued decline in slump values is linked to the fibrous network that enhanced cohesiveness and restricted flow, as reported in [24, 25]. Table VI illustrates the details of the fresh and hardened concrete test results.

TABLE VI. FRESH AND HARDENED CONCRETE TEST RESULTS

Mix	**Slump cm**	**Cube compressive strength**		**Splitting tensile strength**		**Flexural strength**	
		Mean ± SD (MPa)	**eff (%)**	**Mean ± SD (MPa)**	**eff(%)**	**Mean ± SD (MPa)**	**eff(%)**
N	11	36.53±8.1	-	3.1±0.17	-	4.8±1.37	-
S1	4.5	69.5±1.26	90	5.7±0.92	83.9	6.1±1.29	27
S0.5	6	70±1.51	91.6	4.8±0.38	54.8	5.7±0.5	18.8
T1	3	51.9±6.72	42	5.5±0.26	77	6.9±1.81	43.8
T0.5	6	48±7.9	31.4	4.7±0.7	51.6	5.2±2.17	8.3
P1	5	42.4±5.31	16	3.36±0.55	8.4	4±0.46	-16.7
P0.5	6.5	42.53±3.7	16.4	2.8±0.12	-9.7	3.9±0.66	-18.8
E1	6.5	44.8±2.61	22.6	3.7±0.57	19.4	3.5±0.95	-27
E0.5	8	44.13±7.2	20.8	3.33±0.53	7.4	4.3±1.58	-10.4

a. eff: strength-effectiveness (%) (eff (%) = $\frac{fmix-fN}{fN}$ ×100)

b. SD: Standard Deviation (SD = $\sqrt{\frac{\Sigma(x_i - \bar{x})^2}{(n-1)}}$)

Fig. 8. Workability test of concrete mixtures.

B. Hardened Concrete

1) Compressive Strength Test

The compressive strength test was evaluated after 28 days of curing of the cube specimens (Figure 9) [26]. Three cubic samples for each mixture were cast, demolded after 24 h, and then cured for 28 days in water before testing. A compression testing machine was used to apply an axial load on concrete until failure. The test findings are summarized in Table VI, whereas Figure 10 shows the average results for the three tested samples.

Fig. 9. Compressive performance of concrete mixtures.

Normal concrete exhibits a compressive strength of 36.53 MPa. The results indicated that compared to normal concrete, the recycled tire steel fiber mixture tends to enhance compressive strength by 31.4% and 42% for T0.5 and T1, respectively, due to their random orientation and rough surface texture, which improves mechanical interlock with the matrix, as proposed in [27]. Steel fibers increased the efficiency of compressive strength by 90% and 91.6% for S1 and S0.5, respectively. This is mainly attributed to their ability to bridge micro-cracks and provide confinement, especially at optimized fiber volumes and aspect ratios [28]. The impact of PP fibers on compressive strength is minimal, especially at higher dosages (>0.5%), with a compressive strength effectiveness of 16% for P1. Plastic fibers had a modest effect on compressive strength, with 22.6% and 20.8% increase for E1 and E0.5, respectively. This could be a result of weak fiber–matrix bonding and potential voids introduced during mixing [29]. According to the results, fiber quantities must be carefully chosen, and fibers must be evenly spread throughout the mixture.

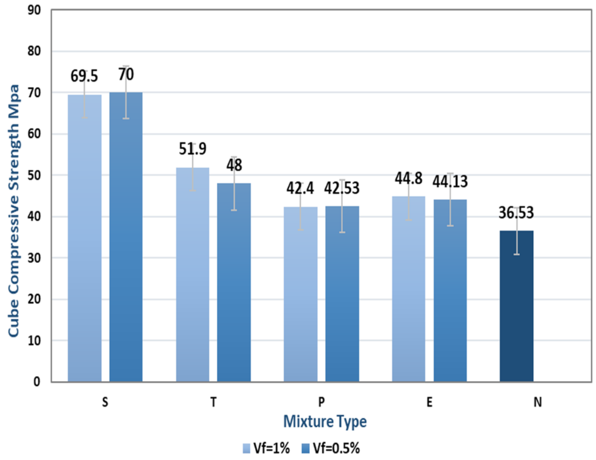


Fig. 10. Cube compressive strength performance results.

2) *Splitting Tensile Test*

Cylindrical specimens of 100×200 mm (Figure 11) were tested to examine the splitting tensile strength at 28 days of curing [30]. In general, the incorporation of fiber shows enhanced post-cracking behavior, as exhibited in Table VI and Figure 12, where the embedded fibers bridge cracks and provide tensile resistance beyond the cracking point. This led to an increase of splitting tensile strength up to 83.9%, depending on fiber type, volume fraction, and distribution. Normal concrete, in contrast, exhibits brittle behavior under tensile stress, with a sudden failure once cracking initiates. Recycled fibers show promise for sustainable applications, with mechanical benefits varying according to fiber processing and dosage. Recycled tire fibers exhibit strength effectiveness of 77% for T1, and 51.6% for T0.5 [31]. PET fibers demonstrated strength effectiveness of 19.4% for E1, and 7.4% for E0.5, consistent with [29]. Steel fibers often provide the most significant enhancement, increasing tensile strength effectiveness to 83.9% for the S1 mixture, and 54.8% for S0.5 due to their high stiffness and crack-bridging ability. In contrast, P1 fibers exhibited a low improvement of 8.4%, while reducing V_f to 0.5% lead to a tensile strength decrease of 9.7% for P0.5.

The findings indicate that stress is transmitted to the fibers. By inhibiting the propagation of macrocracks, the fibers can enhance the splitting tensile strength, with the level of improvement significantly varying depending on the fiber type and V_f.

Fig. 11. Cylinder specimens under splitting tensile load.

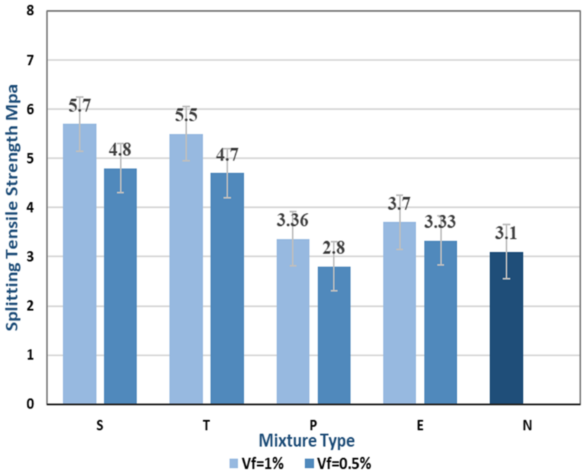


Fig. 12. Influence of fibers on concrete splitting strength.

3) *Flexural Strength Test*

Flexural strength was evaluated at 28 days of curing by the third-point loading method on beam specimens with dimensions of 100×100×40 mm (Figure 13), according to [32]. In conventional concrete, which lacks any reinforcing fibers, the flexural strength is primarily governed by the compressive strength and matrix integrity of the concrete, with a measured value of 4.8 MPa, and failure occurring in a brittle manner once the crack initiates. The experimental results (Table VI and Figure 14) indicate that the incorporation of recycled tire fibers and steel fibers improves the flexural strength, due to the bridging action of fibers across cracks, compared to normal concrete samples.

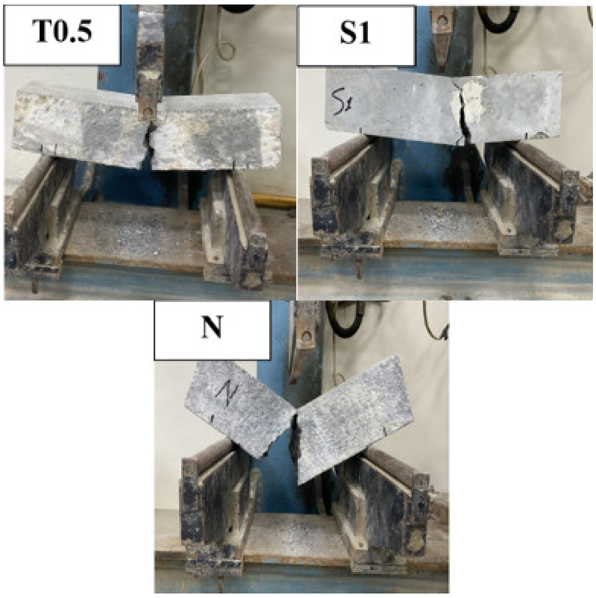


Fig. 13. Flexural test performance.

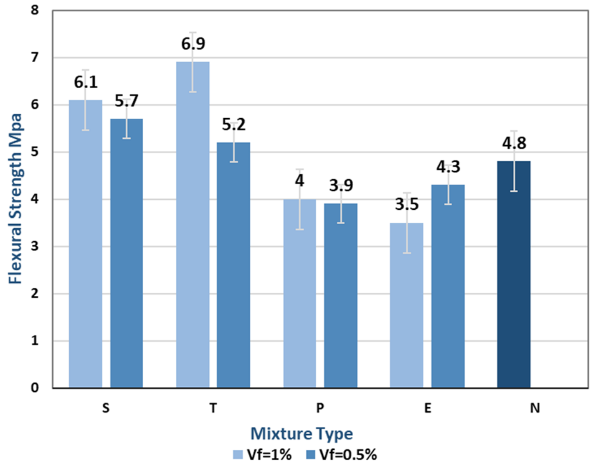


Fig. 14. Flexural test outcomes for different mixed proportions.

Recycled tire fibers can increase flexural strength effectiveness by 43.8% and 8.3% for T1 and T0.5, respectively, attributed to efficient crack-bridging and stress transmission across crack faces, complying with the findings of [33]. Steel fiber addition of 0.5% and 1% by volume generally resulted in moderate improvements of 27% and 18.8%, respectively. On the contrary, samples reinforced with PET and PP suffered from a loss in flexural strength effectiveness compared to normal concrete. The negative effect on flexural strength is attributed to weak fiber-matrix bonding, low fiber aspect ratios for E, and reduced elastic modulus. The relatively low aspect ratio for E fibers explains, in part, the limited flexural performance of E-reinforced mixes. High-modulus fibers influence both the maximum flexural strength, by preventing crack initiation, and the post-peak load-bearing capacity through effective stress transfer. In contrast, low-modulus fibers (E, P) boost post-crack performance, improving ductility and energy absorption, but their impact on peak strength is negligible [34, 35]. Relative to normal concrete, flexural strength effectiveness increases with splitting tensile strength effectiveness, following a quadratic correlation ($R^2 \approx 0.84$). Lower values for E and P mixtures indicate that these fiber-reinforced mixes underperform compared to the reference mix, as illustrated in Figure 15.

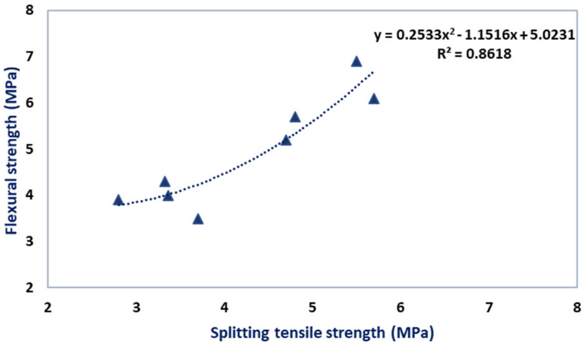


Fig. 15. Correlation between flexural strength and splitting tensile strength.

IV. CONCLUSION

The experimental findings and observations in this work allow for the deduction of the following conclusions:

- This study introduces an eco-friendly approach by incorporating Recycled Polyethylene Terephthalate (R-PET) fibers and recycled tire steel fibers into concrete at V_f of 0.5 and 1%, to balance sustainability and mechanical performance. These were benchmarked against industrial micro straight steel fibers, Polypropylene (PP) fibers, and a normal concrete control mix.
- The use of fibers derived from recycled waste offers sustainability advantages, including waste diversion and reduced raw material use.
- Low-cost recycled materials can reduce waste accumulation while improving the properties of the concrete mixture.
- According to the experimental findings, adding fibers often decreased workability (slump value), with higher fiber volume fractions causing greater reduction. The maximum decrease was observed for T1 (73%) and the minimum for E0.5 (27.3%).
- Most of the Fiber-Reinforced Concrete (FRC) mixtures showed improvements in mechanical properties compared to normal concrete, enhancing one or more of compressive, tensile, and flexural strengthσ, with the highest improvements observed in the case of the micro straight steel fiber.
- The best compressive strength performance was observed at a V_f of 1% for R-PET fibers and waste scrap tire fibers,

whereas for both industrial fibers, micro straight steel fibers and PP fibers, the best behavior was recorded at a V_f of 0.5%.

- The splitting tensile strength effectiveness increased with a fiber volume fraction of 1% for all fiber-enhanced concrete mixtures compared to normal concrete, with a maximum value of 77% for T1, and 83.9% for the S1 mixture.
- Utilizing recycled scrap tire fibers and micro straight steel fibers improved the concrete mixture flexural strength, with a maximum effectiveness of 43.8% for the T1 mixture, compared to normal concrete. However, this improvement decreased with lower V_f of the fiber. In contrast, both R-PET fibers and PP fibers, negatively affect flexural strength, due to the weak connection of the fibers with the cement matrix, low elastic modulus of the fiber, and increased porosity.

Overall, the results revealed that among the FRC mixtures, recycled tire fibers and micro straight steel fibers showed the best convergent improvement in mechanical performance, especially with a V_f of 1%.

V. FUTURE WORK

Future research should focus on: (1) microstructural characterization through SEM and fiber pullout tests to quantify interfacial bond strength; (2) wider ranges of fiber volume fractions and systematic hybrid fiber combinations; (3) durability assessment including corrosion resistance, freeze-thaw, and chemical attack; (4) instrumented testing for load-displacement curves and toughness parameters; (5) structural-scale specimen tests to validate the findings and assess size effects; and (6) comprehensive cost-benefit and life-cycle analyses to support practical implementation in sustainable construction.

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