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Utilization of Polymeric Waste Materials in Fiber-Reinforced Concrete for Sustainable Road Pavement Construction

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Abstract: *The growing accumulation of polymeric waste—especially polyethylene plastics and scrap tires—poses a significant threat to environmental sustainability. This study explores the use of these waste materials as reinforcing fibers in concrete, aiming to enhance mechanical performance while promoting eco-friendly construction practices. Polyethylene fibers were sourced from recycled milk packaging, and tire fibers were processed from discarded automobile tires. Both were cleaned, cut to uniform sizes, and incorporated into concrete mixes of grades M30, M35, and M40 at optimized volume fractions. The experimental program included tests for compressive, flexural, and shear strength, as well as load-deflection behavior. Results showed that fiber-reinforced concrete (FRC) achieved strength gains of up to 17.93% in compression, 39.70% in flexure, and 32.72% in shear compared to conventional concrete. Additionally, deflection reductions up to 39% were recorded, indicating improved ductility and crack resistance. Theoretical deflection models underestimated the true stiffness of FRC, highlighting the need for refined design approaches. The study concludes that recycled polymer fibers can significantly improve the structural performance of concrete while simultaneously reducing environmental impact. Their application in pavement construction demonstrates a viable route for integrating sustainability into civil infrastructure, supporting circular economy and waste reduction goals.*
Keywords: *Fiber-Reinforced Concrete (FRC); Polyethylene Waste; Tire-Derived Fibers; Sustainable Pavement; Recycled Construction Materials.*

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I. Introduction

The rapid pace of urbanization and infrastructure development has significantly increased the demand for durable, cost-effective, and sustainable construction materials. Traditional concrete, though widely used, exhibits inherent limitations such as brittleness and low tensile strength, making it vulnerable to cracking under dynamic loads and environmental stressors. To overcome these challenges, the use of fiber-reinforced concrete (FRC) has gained widespread attention. FRC incorporates various types of fibers into the concrete matrix to enhance its mechanical performance, particularly in terms of tensile strength, ductility, and crack resistance (ACI 544.1R-96, 1996).

Among the types of fibers used, synthetic fibers such as steel, polypropylene, and polyethylene have proven especially effective in improving the toughness and durability of concrete structures. Steel fibers offer high tensile strength and are commonly used in industrial pavements, bridge decks, and tunnels. However, their susceptibility to corrosion limits their longevity in aggressive environments (Mindess et al., 2003). Polypropylene fibers, on the other hand, are hydrophobic and chemically inert, making them useful in controlling plastic shrinkage and early-age cracking, especially in hot climates (Zhang & Li, 2020).

A growing area of interest is the utilization of waste-derived polymer fibers, particularly polyethylene (PE) from packaging waste and fibers from end-of-life tires. Polyethylene waste is among the most commonly discarded plastics, often found in shopping bags, food containers, and milk pouches. Due to its high resistance to degradation, polyethylene persists in the environment for hundreds of years, contributing significantly to plastic pollution (Geyer et al., 2017; Hopewell et al., 2009). Likewise, tire waste, which consists of synthetic rubber and steel reinforcements, accumulates in landfills and poses risks of fire hazards and leachate contamination (ETRMA, 2021; Bocca et al., 2009).

In this context, recycling polymeric waste into FRC presents a dual opportunity: improving the mechanical performance of concrete while diverting non-biodegradable materials from landfills. Previous research has shown that polymeric fibers, especially those derived from waste streams, can enhance flexural and shear strength, reduce crack widths, and extend service life in pavement applications (Islam et al., 2021; Khalid et al., 2022). Their low density and chemical resistance also contribute to better durability and resilience under adverse environmental conditions.

This study aims to build upon these findings by experimentally evaluating the mechanical behavior of FRC incorporating polyethylene and tire-derived fibers. It focuses on performance metrics such as compressive strength, flexural strength, shear strength, and deflection behavior under load for concrete mixes of varying grades (M30, M35, M40). By comparing the results with conventional concrete and theoretical models, this work intends to provide both practical insights and theoretical justification for the widespread adoption of waste-based fiber reinforcement in road pavement construction.

II. Literature Review

In recent decades, the incorporation of polymers into pavement construction has emerged as a promising solution to enhance the mechanical performance and longevity of road infrastructure. Polymers, both synthetic and recycled, have been utilized in various forms—such as surface coatings, binder modifiers, and fiber reinforcements—to improve the structural behavior of concrete and asphalt. Studies have shown that polymer-modified binders and fiber-reinforced concretes exhibit improved resistance to rutting, thermal cracking, and fatigue under repeated loading conditions (Shukla et al., 2019; Rahman & Wahid, 2021).

Fiber-reinforced concrete (FRC) is particularly effective in addressing the brittleness and cracking behavior of conventional concrete. The inclusion of discrete fibers helps in redistributing stresses and bridging micro-cracks, leading to enhanced tensile strength, toughness, and post-crack load-bearing capacity (ACI Committee 544, 2018). Among various types of fibers, synthetic ones—such as polypropylene (PP), polyethylene (PE), and polyester—are favored for their corrosion resistance, durability, and cost-effectiveness. Polypropylene fibers have been widely studied for their ability to control early-age cracking and improve fatigue resistance in pavement-grade concrete (Zhang & Li, 2020).

Recycled polymer fibers, particularly those sourced from post-consumer waste, have gained increasing attention due to their environmental benefits and satisfactory mechanical performance. For example, waste polyethylene fibers, derived from used milk pouches and plastic packaging, have been shown to improve crack resistance, shrinkage control, and impact strength of concrete when added in small percentages (Islam et al., 2021). Similarly, tire-derived fibers have demonstrated significant potential in enhancing shear strength and deflection behavior, especially in pavement slabs exposed to high traffic loads (Khalid et al., 2022).

Several studies have focused on the sustainability aspect of using polymeric waste in concrete. Ali et al. (2023) highlighted that integrating polyethylene and polypropylene waste into concrete not only improves ductility and energy absorption but also reduces the environmental footprint by diverting plastics from landfills. Gencel et al. (2023) explored the hybrid use of steel and synthetic fibers, concluding that such combinations offer superior toughness and fatigue resistance, although challenges in uniform dispersion and field application remain.

Xu et al. (2021) emphasized the long-term mechanical durability of polymer FRC under environmental stressors, finding that PE and PP fibers significantly delayed crack propagation and increased service life. However, other studies, such as that by Bhuiyan et al. (2022), have pointed out limitations in polymer fiber usage, including reduced compressive strength at high fiber volumes and variability in performance depending on waste quality and fiber geometry.

Despite these limitations, the overall consensus in literature supports the integration of polymeric waste fibers into concrete as a viable approach to improve performance while achieving sustainability goals. The reuse of such materials aligns with circular economy principles and United Nations Sustainable Development Goals (SDG 11 and 12), emphasizing responsible production and sustainable infrastructure.

This review underscores the relevance of further empirical research to validate theoretical claims and develop standardized processing methods for polymeric fibers. It also highlights the need to bridge gaps in lifecycle assessment, fiber-matrix interaction mechanisms, and field-scale implementation, forming the foundation for the present study.

III. Materials and Methods

3.1 Materials Used

This study utilized a combination of conventional concrete constituents and recycled polymer fibers to produce fiber-reinforced concrete (FRC) (see Table 1). The core materials included Ordinary Portland Cement (OPC), fine and coarse aggregates, potable water, a superplasticizer admixture, and polymeric fibers derived from polyethylene waste and scrap tires.

OPC of 43 or 53 grade, conforming to IS 12269 specifications, was used as the primary binder. The cement ensures adequate early and long-term strength development in concrete. Potable water, free from harmful impurities such as chlorides and sulfates, was employed to facilitate the hydration process. For fine aggregates, well-graded river sand or crushed stone sand passing through a 4.75 mm sieve was used to enhance the concrete's workability and minimize voids.

Coarse aggregates consisted of a mix of 10 mm and 20 mm angular crushed stones. These aggregates contributed to the bulk and strength of the concrete, improving compaction and internal load distribution. A high-range water-reducing admixture (superplasticizer) was incorporated to improve the flow and uniform fiber dispersion without altering the water–cement ratio.

The key innovation in the material composition involved the inclusion of recycled polymeric fibers. Polyethylene fibers were sourced from discarded OMFED milk pouches, which were cleaned, air-dried, and shredded into strips measuring 25–40 mm in length. Tire-derived fibers were obtained from processed scrap tires, with embedded steel wires removed before cutting them into fibers approximately 30–50 mm in length. These fibers were added to the mix at 0.5% to 1.0% by volume.

Table 1. Materials Used in Fiber-Reinforced Concrete

Material	Description
Cement	Ordinary Portland Cement (OPC) 43/53 grade, as per IS 12269.
Water	Potable water, free from impurities; ensures proper hydration.
Fine Aggregates	River sand or crushed stone sand (≤ 4.75 mm); improves workability.
Coarse Aggregates	10 mm and 20 mm angular aggregates; provide compressive strength and bulk.
Superplasticizer	Used to enhance workability and fiber dispersion; dosage per mix trials.
Polyethylene Fibers	Sourced from OMFED milk pouches; washed, shredded to 25–40 mm length.
Tire-Derived Fibers	Scrap tires processed; steel removed; fibers cut to 30–50 mm length.

3.2 Mix Design (M30, M35, M40)

Concrete mixes of three different grades—M30, M35, and M40—were prepared according to IS 10262:2019 and IS 456:2000 guidelines. The water–cement ratio was adjusted based on the required grade strength: 0.45 for M30, 0.43 for M35, and 0.40 for M40. The mix proportions were optimized through trial batches to ensure workability and fiber dispersion. The binder-aggregate ratio, aggregate gradation, and superplasticizer dosage were calibrated to achieve a slump of 75–100 mm. Fiber-reinforced concrete was prepared by adding 0.5% to 1.0% volume fraction of polyethylene and tire fibers into each mix grade.

3.3 Specimen Casting and Curing

Concrete was mixed in a mechanical mixer. Dry materials, including the fibers, were mixed first to ensure even distribution. Water mixed with the superplasticizer was gradually added to achieve a uniform and workable consistency. The mix was poured into steel molds—cubes (150×150×150 mm), beams (100×100×500 mm), and shear specimens—and compacted using a vibrating table. After 24 hours, the specimens were demolded and submerged in water for 28 days of standard curing.

3.4 Testing Methods

The mechanical performance of both conventional and fiber-reinforced concrete was evaluated through:

- **Compressive Strength Tests** on 150 mm cubes, in accordance with IS 516:1959.
- **Flexural Strength Tests** using a 4-point bending setup on beam specimens.
- **Double Shear Tests** to determine shear strength and post-cracking behavior.
- **Load-Deflection Measurements** using dial gauges and LVDTs during flexural and shear loading to assess ductility and energy absorption capacity.

IV. Results and Discussion

4.1 Compressive Strength

The compressive strength results, as summarized in Table 2, demonstrate a clear enhancement in performance due to the incorporation of polymeric fibers. For all three concrete grades—M30, M35, and M40—the fiber-reinforced concrete (FRC) specimens exhibited higher compressive strengths compared to their conventional counterparts. Specifically, M30-grade concrete showed an increase from 37.18 N/mm² to 43.52 N/mm² (a 17.93% gain), while M35 and M40 grades achieved 15.98% and 16.10% improvements, respectively. These gains can be attributed to the fiber-bridging mechanism provided by polyethylene and tire-derived fibers, which delays crack propagation and enhances load distribution within the matrix (Table 2).

Table 2: Compressive Strength Comparison

Grade	Conventional (N/mm²)	FRC (N/mm²)	Improvement (%)
M30	37.18	43.52	17.93%
M35	42.66	49.63	15.98%
M40	46.96	54.52	16.10%

4.2 Flexural Strength and Ductility

The flexural strength and deflection behavior of the concrete specimens, detailed in Table 3, reveal significant improvements resulting from the incorporation of polymeric fibers. Fiber-reinforced concrete (FRC) exhibited substantial gains in flexural strength across all grades, with M30 increasing from 3.91 N/mm² to 5.37 N/mm² (a 37.34% improvement), M35 rising from 4.02 N/mm² to 5.63 N/mm² (39.70%), and M40 reaching 5.74 N/mm² from 4.20 N/mm² (39.66%). In addition to strength gains, the inclusion of fibers also reduced mid-span deflections, indicating improved stiffness and crack resistance. Deflection reductions were recorded as 22.22% for M30, 23.53% for M35, and 20.78% for M40, underscoring the enhanced ductility and load-carrying capacity of FRC under flexural loading (Table 3).

Table 3. Flexural Strength and Deflection

Grade	Conventional Flexural (N/mm²)	FRC Flexural (N/mm²)	Improvement (%)	Deflection Reduction (%)
M30	3.91	5.37	37.34%	22.22%
M35	4.02	5.63	39.70%	23.53%
M40	4.20	5.74	39.66%	20.78%

4.3 Shear Strength and Toughness

The shear strength results presented in Table 4 highlight the positive impact of polymeric fiber reinforcement on the structural behavior of concrete under shear loading. Across all tested grades, fiber-reinforced concrete (FRC) outperformed conventional concrete in both strength and deformation resistance. For M30 concrete, shear strength increased from 8.58 N/mm² to 11.26 N/mm²—a 31.33% improvement. Similarly, M35 and M40 grades showed increases to 11.42 N/mm² and 11.52 N/mm², reflecting improvements of 32.56% and 32.72%, respectively. Alongside these gains, deflection at failure was significantly reduced, indicating enhanced stiffness and crack-arresting ability. M30, M35, and M40 exhibited deflection reductions of 38.69%, 36.23%, and 33.75% respectively, further confirming the role of fibers in enhancing shear toughness and post-crack behavior (Table 4).

Table 4. Shear Strength and Deflection

Grade	Conventional Shear (N/mm²)	FRC Shear (N/mm²)	Improvement (%)	Deflection Reduction (%)
M30	8.58	11.26	31.33%	38.69%
M35	8.63	11.42	32.56%	36.23%
M40	8.69	11.52	32.72%	33.75%

The combined results shown in Figure 1 clearly illustrate the mechanical strength improvements achieved by incorporating polymeric fibers into concrete. Fiber-Reinforced Concrete (FRC) demonstrated consistently higher performance in all three key mechanical properties—compressive, flexural, and shear strength—across all grades (M30, M35, and M40) when compared to conventional concrete. The figure visually confirms the strength trends detailed in Tables 2, 3, and 4, highlighting the effectiveness of recycled polyethylene and tire fibers in enhancing structural performance. This improvement is especially pronounced in flexural and shear capacities, which are critical for pavement applications requiring toughness and crack resistance (Figure 1).

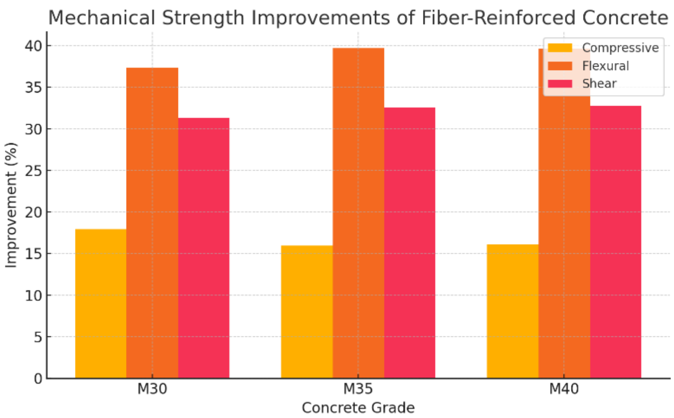

Figure 1. Mechanical Strength Improvement of FRC

4.4 Deflection Behavior: Theory vs. Experiment

The comparison between theoretical and experimental deflection data revealed notable differences, particularly for fiber-reinforced concrete (FRC). While conventional concrete displayed good agreement with classical elastic beam theory—deviations typically below 12%—FRC exhibited larger discrepancies, with deflection variations reaching up to 19.31% in flexure and 16.98% in shear. This divergence is primarily attributed to the nonlinear, heterogeneous, and ductile behavior introduced by fiber inclusion, which is not captured by traditional linear-elastic models. The bridging and pull-out mechanisms of polymeric fibers contribute to increased energy absorption and delayed crack propagation, resulting in higher stiffness and reduced deflections in practice than predicted theoretically. These findings indicate the need for refined analytical models that consider the composite nature and strain-hardening behavior of FRC systems.

4.5 Summary of Mechanical Performance Trends

The overall mechanical performance of fiber-reinforced concrete significantly exceeded that of conventional mixes across all strength grades. Compressive strength improved by approximately 16–18%, while flexural and shear strength showed even higher enhancements, exceeding 30% and nearing 40% in some cases. The inclusion of polymeric fibers not only enhanced load-bearing capacity but also significantly reduced deflections under both flexural and shear loading conditions, indicating improved ductility, toughness, and post-crack stability. This consistent performance across M30, M35, and M40 grades confirms the effectiveness of recycled polyethylene and tire fibers in reinforcing concrete for demanding structural applications, especially in pavements exposed to heavy and repetitive loading.

V. Environmental and Sustainability Assessment

The integration of polymeric waste into concrete serves a dual purpose: enhancing mechanical performance while addressing environmental sustainability. The reuse of polyethylene packaging and scrap tire rubber in civil infrastructure applications directly contributes to waste reduction, minimizes the need for virgin materials, and reduces environmental hazards associated with landfilling and incineration. In line with global sustainability goals, fiber-reinforced concrete using recycled polymers aligns with efforts to reduce the carbon footprint of the construction industry while promoting green material practices.

5.1 Waste Diversion Benefits

The diversion of polymeric waste from landfills is one of the most impactful benefits of this study. Polyethylene, which is slow to degrade and often ends up as microplastics in ecosystems, can instead be redirected to enhance concrete performance. Similarly, tire waste, which is bulky and hazardous due to its composition and flammability, can be transformed into a valuable construction input. By reusing these materials in concrete production, the study supports a large-scale, practical solution for addressing the ever-growing problem of plastic and rubber waste accumulation.

5.2 Energy and Resource Savings

Using recycled polymer fibers in concrete conserves substantial amounts of energy and raw materials. Traditional synthetic fibers require energy-intensive manufacturing processes involving petrochemicals, whereas recycling existing waste bypasses those steps. Additionally, replacing portions of traditional concrete reinforcement with waste-derived fibers reduces the need for steel and virgin polymers, lowering overall embodied energy. This contributes to a more energy-efficient and environmentally responsible construction process, especially relevant in infrastructure development.

5.3 Alignment with Circular Economy Goals

This research supports the principles of a circular economy by transforming waste into a functional resource within the construction industry. Rather than being discarded, polyethylene and tire waste are reprocessed and reintegrated into the economic cycle, aligning with Sustainable Development Goals (SDGs) such as SDG 11 (Sustainable Cities and Communities) and SDG 12 (Responsible Consumption and Production). The reuse of waste materials not only minimizes environmental impact but also demonstrates how engineering innovation can promote material circularity and resilience in infrastructure.

VI. Conclusions and Recommendations

The findings from this study affirm that recycled polyethylene and tire fibers can be effectively used in concrete to enhance its mechanical properties and serviceability. The improvements in compressive, flexural, and shear strength, as well as the significant reductions in deflection, demonstrate that fiber-reinforced concrete (FRC) made with polymeric waste is structurally viable for demanding applications such as road pavements. Beyond the technical gains, this approach contributes to waste management and environmental sustainability, presenting a compelling case for broader adoption in the construction industry.

The research demonstrated that the inclusion of polymeric waste fibers—specifically polyethylene from packaging and steel-free tire shreds—substantially improved the mechanical performance of concrete. Increases of up to 17.93% in compressive strength, 39.70% in flexural strength, and 32.72% in shear strength were observed. In parallel, deflection under loading was significantly reduced, enhancing ductility and energy absorption. These improvements were consistent across all mix grades studied (M30, M35, M40), highlighting the reliability of fiber reinforcement across structural performance tiers.

The practical application of polymeric FRC is especially promising in road construction, overlays, bridge decks, and seismic regions where improved toughness and ductility are critical. This material can offer better crack control and longer service life in pavements subject to dynamic loads. Moreover, using waste-derived fibers can lower material costs and contribute to more sustainable project delivery, particularly beneficial in resource-constrained or environmentally sensitive areas.

It is recommended that local bodies and construction agencies consider the integration of waste-based FRC into standard pavement specifications. Standardizing fiber sizes, dosages, and mix procedures can ensure consistency and quality across applications. Pilot-scale road segments using polymeric FRC should be deployed to evaluate field performance under real traffic conditions. Guidelines for safe handling, storage, and quality control of recycled fibers should also be developed.

While this study focused on short-term mechanical performance, future research should explore the long-term durability of polymeric FRC under environmental exposures such as freeze-thaw cycles, sulfate attacks, and UV degradation. Life-cycle assessments (LCAs) and cost-benefit analyses can further quantify the environmental and economic advantages. Additionally, research into hybrid fiber systems, automation of fiber processing, and digital design tools for FRC structures will support the evolution of this sustainable construction material.

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