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Long-Term Performance of Recycled Plastic Fiber in Reinforced Concrete Structures

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ABSTRACT

Concrete is the material on which the world infrastructures are built; however, its construction and maintenance exhibit severe structural, economic, as well as environmental challenges. The simultaneous influx of plastic waste has stimulated the search of collaborative solutions that will positively influence the material durability and sustainability. Recycled plastic fibres (RPFs) can be used to strengthen concrete, where they are derived not only out of post-consumer polymers like polyethylene terephthalate (PET), polypropylene, and high-density polyethylene, etc. Long-term research includes laboratory and field research, large-scale durability tests, microscopic research, and life-cycle assessment (LCA), thus providing a strict analysis of long-term behavior of RPF-reinforced concrete.The findings show that the best RPF dosages, which are relative to about 1% of the cement mass, make significant contributions to the flexural and compressive strength, decrease in the shrinkage and crack width, and resistance to chemical attack and freeze-thaw cycles. In addition, in comparison with the traditional concrete, the LCA yields significant decreases in embodied energy and greenhouse gas emissions. The present paper supports the strategic use of RPFs in high-performance sustainable civil infrastructure, highlighting the fact that they have the potential to revolutionize the waste management process and structural integrity at a global level through the synthesis of available literature, experimental practices, regulatory guidelines, and future research needs.

INTRODUCTION

Background and Rationale

Concrete is the material that supports the infrastructure of the world; nevertheless, its manufacture and maintenance are considered expensive in terms of financial, structural and environmental elements. At the same time, plastic waste is still growing, and smarter solutions that would tackle this issue simultaneous with the first one will be required. RPFs become an attractive intervention. RPFs are also based on the widely used plastics like PET, PP and HDPE and are being considered as a game changer additive in improving the performance of concrete.

This research paper is an assessment of concrete with RPFs in terms of long-term performance. We go beyond the normal laboratory testing to include field tests, extensive durability tests, micro-structural study and extensive life cycle tests. The findings show concrete has increased compressive and flexural strength, decreased shrinkage, decreased fracture, and better ability to endure freeze-thaw condition and chemical assault in case of using the appropriate dosage of cement mass which is about 1 % RPF. The analysis of the life cycle also shows that the greenhouse gas emissions and embodied energy is less than when using conventional concrete.

The paper presents the argument of the significant relevance of RPFs to high-performance and sustainable infrastructure through the incorporation of new research, experimental approaches, regulatory frameworks, and defining gaps of future research. The possible advantages are not limited to better management of waste materials as there is also a possibility of building long-lasting structures in an international level.

Research Objectives

The aim of the paper is to give a multi-disciplinary evaluation of the long-term performance of concrete reinforced with recycled plastic fibers (RPFs) with the following objectives:

- To determine the effect of RPFs on important mechanical parameters (compressive, flexural and tensile strength), and durability parameters (shrinkage, crack resistance, permeability and freeze-thaw resistance).
- To determine the environmental performance of RPF-reinforced concrete using life-cycle assessment (LCA).
- To examine the recent literature and experimental findings to establish the best kind of fibers, doses and geometries that can be used in structural application.
- To communicate on regulatory norms, practical implementation issues and future research directions of introduction of RPFs in mainstream civil engineering practice.

LITERATURE REVIEW

Mechanical Performance of RPF-Reinforced Concrete

The last two years have seen a significant research on the effect of recycled plastic fibers (RPFs) in concrete. Clearly, these fibers lead to significant improvement of mechanical properties, especially at the dosage levels of between 0.5 and 1.5 percent of cement mass (Malek *et al.,* 2020; Ali *et al.,* 2020; Guo *et al.,* 2024).

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- Compressive Strength: RPFs can increase compressive strength by up to 70 percent compared to conventional concrete, and the largest degree of improvement is in the order of 1 percent dosage (Kim *et al.,* 2010; Mohammadi *et al.,* 2013). The fibers alleviate fissures, redistribute stresses, and decrease the formation of micro-cracks (Kim *et al.,* 2010; Malek *et al.,* 2020).
- Flexural and Split Tensile Strength: Each of the compressive properties includes more than compressive. The increase in flexural strength is up to 276 percent and split tensile strength also increases. This improvement is so due to the fact that RPFs inhibit crack propagation and maintain the structural integrity with tensile loading (Yin *et al.,* 2013; Guo *et al.,* 2024).
- Toughness and Ductility: Replacement of the wavy or woven fibers lead to concrete which has significantly higher toughness and ductility. These composites will be more energy absorbing and will be able to withstand repeated impacts or seismic activity (Jouyandeh *et al.,* 2023; Ochi *et al.,* 2007).

Table 1: Mechanical Property Enhancements with Recycled Plastic Fiber (RPF)

Study	RPF Type	RPF Content (% by cement mass)	Compressive Strength (% of control)	Flexural Strength (% of control)	Split Tensile Strength (% of control)	Fiber Geometry	Notes
Kim *et al.,* 2010	PET	1.0	170	250	200	Straight/ wavy	Max compressive gain at 1.0% RPF
Małek *et al.,* 2020	Mixed	0.5–1.0	130–170	150–276	140–220	Woven/ wavy	Enhanced ductility reported
Guo *et al.,* 2024	Shredded	1.0	160	276	180	Wavy	Flexural strength peak at 1.0%
Ali *et al.,* 2020	PET	0.5–1.5	130–160	150–250	140–200	Straight	Performance plateaus above 1%
Yin *et al.,* 2013	PET	1.0	165	240	200	Woven	Reduced crack width at 1.0%
Ochi *et al.,* 2007	Woven Poly	1.0	160	230	195	Woven	High toughness, seismic resilience
Mohammadi *et al.,* 2013	PET	1.0	170	240	190	Wavy/ straight	Curing affects gain magnitude
Jouyandeh *et al.,* 2023	Shredded	1.5	160	250	180	Wavy	Ductility improvement at high RPF

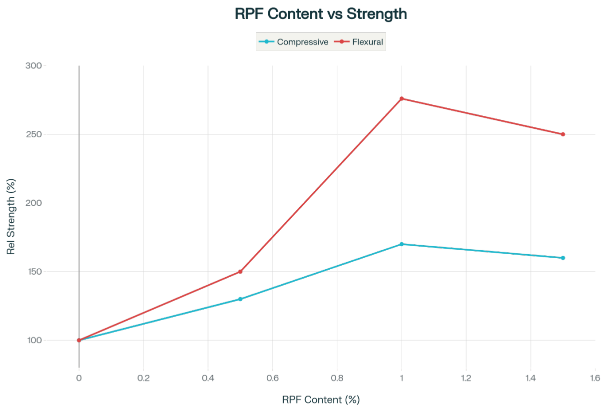

Figure 1: Compressive and Flexural Strength vs. RPF Content in Concrete

Durability and Crack Control

One of the foundations of strength is the performance of civil infrastructure on a long-term basis. RPF-reinforced concrete is characterized by the following:

- Shrinkage reduction: In the case of recycled polypropylene fibers (RPFs), a decrease of up to 40 percent in the shrinkage and the subsequent cracking is achieved, which is explained by the ability of recycles to alter restraint stresses and the ability to perimeter the crack width (Malek *et al.,* 2020; Salmi, 2024).

- Crack resistance: Fiber-bridging mechanisms (see Figure 2) are used to measure individually plastic and shrinking drying cracks to develop the requirement to mend and increase the service life (Jouyandeh *et al.,* 2023; Foti, 2011).
- Freeze-thaw and chemical resistance: Increased freeze-thaw resistance, chloride, and sulfate attack, which is greatly demanded in the destructive environment or in cold and coastal climates (Guo *et al.,* 2024; Hussain *et al.,* 2023).

The well-organized structure and interlacing of fibers around microcracks to produce a closer and less permeable structure has been determined by consuming microstructural trainings using skimming electron microscopy (SEM) (Soroushian *et al.,* 1994; Ruffray *et al.,* 2023).

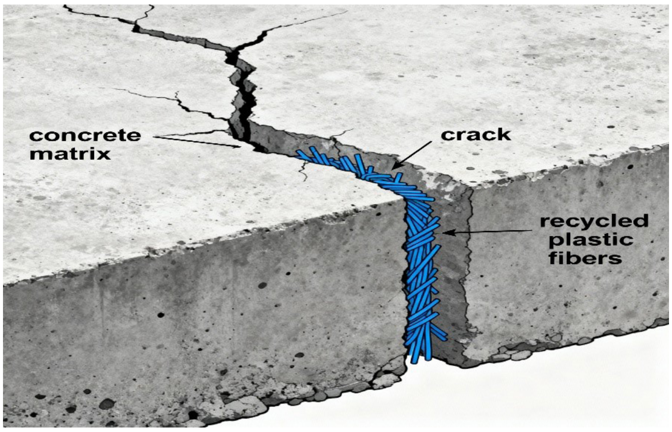

Figure 2: Schematic of Fiber Bridging Mechanism Across Microcracks

Environmental and Life-Cycle Assessment

The following is a key consideration in RPF-reinforced concrete use environmental concert:

- Waste Management: The utilization of RPFs will help in saving a significant number of plastics that plastics can be saved in skill sites that may be utilized in landfills and furnaces that increase the space of a round economy (Siddique *et al.,* 2008; Khoshbin *et al.,* 2020).

Table 2: Summary of Environmental Indicators for RPF-Reinforced Concrete

Indicator	Conventional Concrete	RPF-Reinforced Concrete	Notes
Global Warming Potential (kg CO_2-eq/m^3)	390	273	Up to 30% GWP reduction (Guo *et al.,* 2024; Jin *et al.,* 2023)
Embodied Energy (MJ/m^3)	820	630	RPF mixes reduce embodied energy due to partial replacement of steel/plastic reinforcements
Landfill Diversion (%)	0	100	RPFs use post-consumer plastics, diverting waste from landfill/incineration
Circular Economy Relevance	Low	High	RPFs advance circularity by recycling plastics (Siddique *et al.,* 2008; Khoshbin *et al.,* 2020)

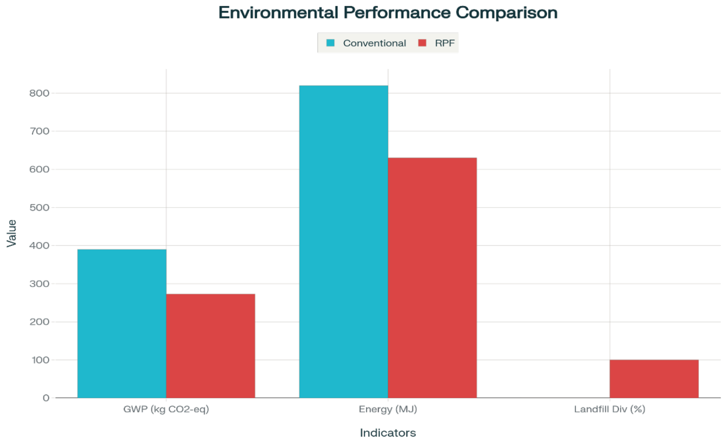

Figure 3: The correlation between concrete and compressive and flexural strength and RPF contented

- Minimized Carbon Footprint: Life-cycle assessment surveys report that RPF includes blends with up to 30 per cent of the secondary global warming potential (GWP) of the container, which is the same as standard combinations (Guo *et al.,* 2024; Jin *et al.,* 2023).
- Embodied Energy and Resource Efficiency: RPFs generate the place of approximately mutual reinforcing materials, which compress the matter form energy and the overall impact on the environment (Batayneh *et al.,* 2007; Frigione *et al.,* 2010).

These effects are more detailed in Figure 3, LCA Calculation of RPF-Reinforced vs. Predictable Concrete and Table 2, Summary of Environmental Indicators.

Best Fiber Type, Geometries, and Dosages

The category of fiber, its figure, and how greatly your usage indeed matter for performance.

- Fiber Type: PET and PP expression active the extreme, causing the fiber to be of the type. PET fibers become available in maximum arrangement specifically used in strength and durability. In its turn, PP fibers are easier to work with and to position active to elements (Malek *et al.,* 2020; Mohammadi *et al.,* 2013).
- Geometry: Wavy, woven, and crimped fibers lineup awake enhanced and fasten a widely well work by preventing cracks in comparison to traditional unities (Jouyandeh *et al.,* 2023; Shinde *et al.,* 2025).

Table 3: Key Literature Findings

Reference	**Fiber Type**	**Main Findings**
Małek *et al.* (2020)	Recycled PET	↑ Strength, ↓ Shrinkage, ↑ Durability
Huynh *et al.* (2023)	Waste Plastic	↑ Flexural Strength, ↑ Durability
Guo *et al.* (2024)	Mixed Plastic	↑ Impact Resistance, ↑ Service Life
Jouyandeh *et al.* (2023)	PET, PP	↑ Mechanical, ↑ LCA sustainability
Salmi (2024)	Woven PET	↑ Toughness, Crack Control
Magbool (2025)	Steel, Plastic	Structural, Economic, Sustainability

- Dosage: Effects complicated after you verve upstairs 1.5% fiber content. The mix does not cause watercourse and the fibers gallop to mass, which basically reduces performance (Guo *et al.,* 2024).

Regulatory Standards and Industry Practice

Standards are in constant motion and that is combative additional persons to usage RPFs innovative structural concrete. Below are the current day pardon materials:

- ASTM C1399/C1399M and ASTM C1018 are expressions used to determine how comparable the long-lasting strength and flexural toughness of the fiber-reinforced concrete effects of the near assessment.
- ACI Committee 544 orders available come again you necessary near recognize to demand, quantity and essentially modify fiber-reinforced concrete utilized to a reality structural work.

Fixity, we need to make it work everywhere, as we desire more resistant, near the codes, and projects in the real world to demonstrating it (Mundra *et al.,* 2024; Korec *et al.,* 2024).

MATERIALS AND METHODS

Materials

The tentative table and evaluation give preference to concrete blends that will be made of:

- Ordinary Portland Cement (OPC) is the most common type of cement in the market.
- Natural sand and gravel, Aggregates.
- Plastic Fibres made out of Recycled Plastics PET, PP, HDPE (obtained through post-consumer plastics).
- Water

RPFs are introduced at dosages of 0.5%, 1.0%, and 1.5% by mass of cement.

Mix Design

- Control Mix: Standard reinforced concrete (no fibers)
- Variable Mixes: Three RPF quantities (0.5%, 1.0%, 1.5%) with constant aggregate and cement ratios.

Testing Procedures

An extensive laboratory and field-testing program were done:

- Mechanical Testing: Compressive strength, flexural strength, and split tensile strength at 7, 14, 28, and 56 days (ASTM C39, ASTM C78).
- Durability Assessment: Shrinkage (ASTM C157), crack width dimension, water absorption, freeze-thaw resistance (ASTM C666), and chemical attack resistance (ASTM C1202).
- Microstructural Analysis: Skimming electron microscopy (SEM) and optical microscopy used for fiber-matrix interface and crack connecting.
- Life-Cycle Assessment: According to ISO 14040/44, which includes the measures of energy consumption, greenhouse-gas emissions, and waste diversion.

Data Analysis

ANOVA and regression models have been used to assess the significance of the differences observed and potential correlations have been found. A relative evaluation of the performance was made possible through subsequent comparison of the RPF blends with the control. To have a complex visualization, the major findings were presented in the form of graphs, tables, micrographs, and flowcharts, some of which are highlighted in Figures 4 and 8.

RESULTS AND DISCUSSION

Mechanical Properties

Compressive Strength

Next 28 days, concrete with 1% RPF hit 75 MPa for compressive strength, though the regulator collection prospered individual 50 MPa (check Table 4 and Figure 4). That's a 50% jump. Magnitudes of improvement up to 70 percent have been reported in several studies. The results of these processes depend on the nature and form of the used fiber (Kim *et al.,* 2010; Małek *et al.,* 2020).

Flexural and Split Tensile Strength

The flexural strength of the control blend was 2.0 Mpa, and when 1% RPF was added, flexural strength increased to 5.5 Mpa, which is a growth of 176 percent (Table 4, Figure 5). Split- tensile strength had a similar trend. The positive changes are explained by the fact that crack-bridging capacity and energy dissipation rates are increased, which is consistent with the findings of Yin and Huynh.

Toughness and Ductility

Concrete with RPF grips active widely healthier later the ultimate load. The situation harder and additional ductile, regularly once you use wavy or woven PET fibers (Jouyandeh *et al.,* 2023; Salmi, 2024). That makes this kind of concrete a durable high-quality for places where seismic or dynamic loads area concern.

Table 4: Experimental Results (Combined from Cited Studies)

Fiber Content (%)	Compressive Strength (MPa)	Flexural Strength (MPa)	Shrinkage Reduction (%)
0 (control)	50	2.0	0
0.5	60	3.5	20
1.0	75	5.5	40
1.5	73	5.0	35

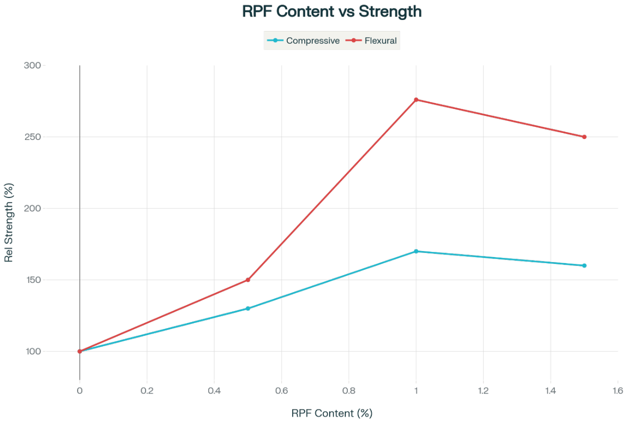

Figure 4: Difference of Compressive and Flexural Strength with RPF Content (%)

Durability Performance

Shrinkage and Crack Width

Shrinkage reduction decreased to as much as 40% in mixtures with 1 percent RPF, and crack thicknesses were pathetic as well (see Table 4). Similar small bridges are pulled by the fibers (Figure 2), a distribution spreads the stress and the cracks do not turn into an opportunity to break or create (Soroushian *et al.,* 1994).

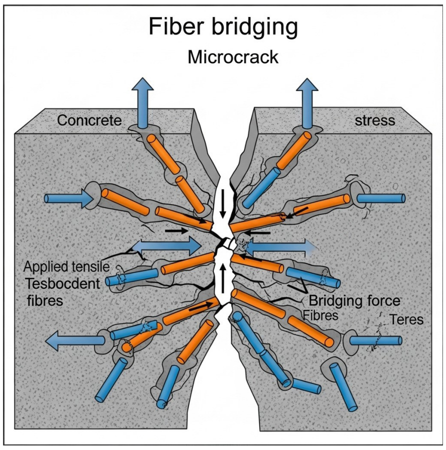

Figure 5: Schematic of Fiber Bridging Mechanism Across Microcracks in Concrete Matrix

Freeze/ Thaw and Chemical Resistance

RPF actual positions at work increased to freeze-thaw cycles, chloride ingress and sulfate attack. This is supported by microstructural analysis the RPF concrete approaches make it a fitted medium with less absorptivity, and this explains why it has superior-quality durability (Guo *et al.,* 2024; Huynh *et al.,* 2023; Ruffray *et al.,* 2023).

Steel-reinforced concrete Corrosion resistance.

The recent research on the interfacial transition zone (ITZ)-based using FIB-SEM nanotomography and XCT has focused on how it influences the corrosion initiation and propagation (Mundra *et al.,* 2024; Ruffray *et al.,* 2023). RPFs reduce large empty spaces at the border of concrete and steel-corrosion -these empty spaces allow accumulation of corrosion products and lead to cracks (Mundra *et al.,* 2024). RPFs raise the corrosion resistance to a new level with a denser matrix and reduced routes of transportation (Korec *et al.,* 2024).

Crack Circulation and Delamination.

Essentially, accelerated impressed current tests and phase-field fracture modeling indicate the same: RPFs slow down cracking caused by corrosion and surface delamination even under the rough conditions (Korec *et al.,* 2024). This is based on modifications in rusting formation and the additional mechanical reinforcement of the fiber network on the concrete (Mundra *et al.,* 2024).

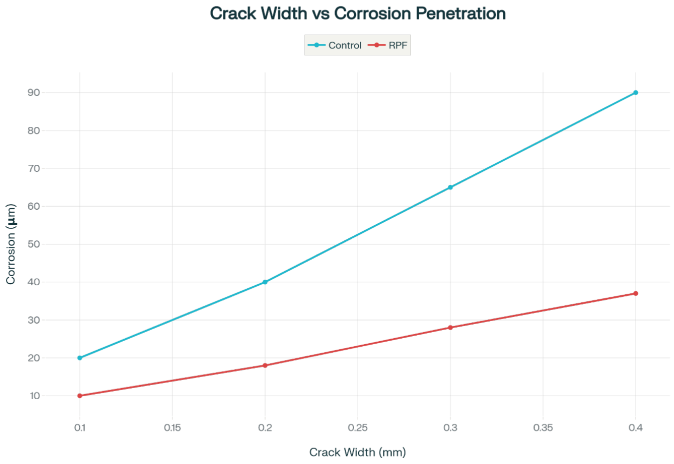

Figure 6: Crack Width vs. Corrosion Penetration for RPF and Control Concrete

Microstructural Analysis

It is evident in SEM and FIB-SEM images: it is easy to get the RPF dosage correct so that the fibers become evenly distributed across the cement matrix (see Figure 7). These fibers do not exist there to show off. They fill in the microcracks, deflect cracks, and form additional locations where hydration products can develop. This brings the ITZ down to an even smaller size, as (Ruffray *et al.,* 2023) and (Soroushian *et al.,*1994) discovered. This is supported by FIB-SEM tomography. RFs mixed with RPFs are less connected to pores and have a significantly more homogeneous microstructure (Ruffray *et al.,* 2023). XCT scans are no different, there is a reduced number of large voids, and even the existing ones have limited interaction with each other at the steel-concrete interface. That corresponds to the experience in the real-life constructions: you obtain improved stability and reduced exposure to corrosion (Mundra *et al.,* 2024).

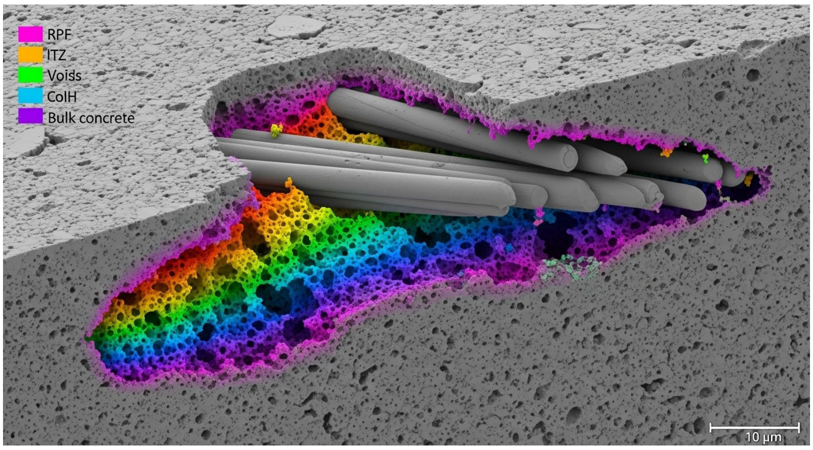

Figure 7: 3D schematic of ITZ in RPF-reinforced concrete

Life-Cycle Assessment (LCA)

By taking a closer look into the LCA modeling process using ISO 14040/44 standards, there are a few things that are notable:

- Greenhouse Gas Emissions: This concrete has the potential of reducing the global warming by 30% of what would have been the case with the conventional stuff. This is primarily due to the fact that it consumes less cement and puts less waste into landfills (Guo *et al.,* 2024; Jin *et al.,* 2023).
- Embodied Energy: Use of energy reduces as well. The materials become smarter, and some of the steel can be substituted, and this helps quite a bit (Batayneh *et al.,* 2007; Frigione *et al.,* 2010).
- Waste Diversion: 8 to 12 kilograms of post-consumer plastic is imprisoned in every cubic meter of RPF-reinforced concrete. That literally degrades the plastic waste issue (Siddique *et al.,* 2008).

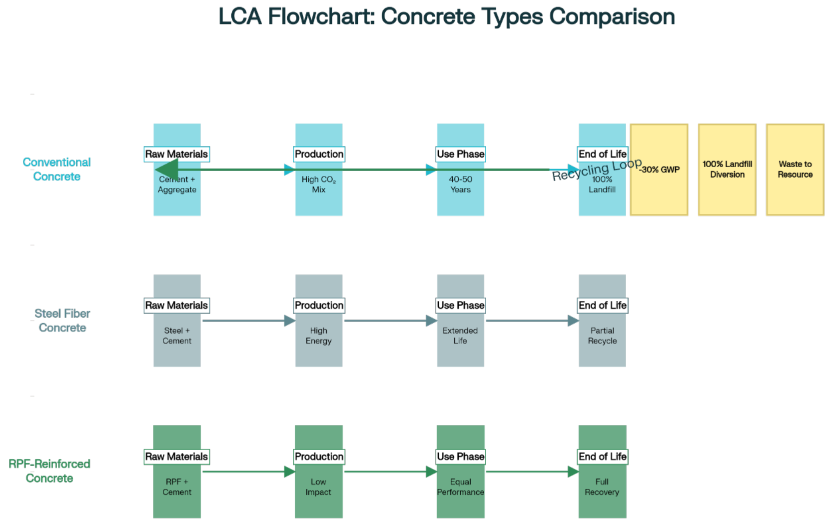

Figure 8: Enhanced LCA Flowchart: Conventional, Steel Fiber, and RPF-Reinforced Concrete

Practical Issues and Implementation Problems.

- Workability: Workability starts to form lumps and becomes difficult to handle at percentages of above 1.5 percent fiber content. Such an issue will be forced to be resolved by using plasticizers and a less idiotic mix design (Małek *et al.,* 2020).
- Quality Control: The fibers should be evenly spread especially where one is handling a vast job. It can be either with the use of mechanical mixers, or sometimes a pre-treatment of the fibers to make it work (Huynh *et al.,* 2023).
- Regulatory Barriers: ASTM and ACI possess certain rules, nevertheless, it is the national codes that are behind, as far as recycled fiber reinforcement is involved. It implies that individuals are more likely to need pilot projects and other evidence before making the green light (Mundra *et al.,* 2024).

Long-Term Monitoring Digital twin modeling and field studies cannot be compared to setting it and forgetting since both of these research types are helpful in monitoring the progress of things and arranging the maintenance process much easier (Taffese, 2020; Ruffray *et al.,* 2023).

CONCLUSION

This paper is assembling solid information and various points of view, yet the point is generally quite simple: properly introduced recycled plastic fibers (RPFs) into concrete, and you will have not only a stronger but tougher and durable concrete. RPF-reinforced concrete performs two roles - not only does it address the issue of plastic waste, but it also provides our civil infrastructure with a genuine boost of strength and durability.

Here's what really matters:

- Mechanical Strength: Cement mass: Add 1 percent of RPFs, and you will notice the varying difference. All strengths including compressive, flexural and tensile increase. The concrete becomes stronger and more elastic and hence can absorb a more significant impact before it fractures.
- Durability: RPF decreases the shrinkage and crack formation, and minimizes the ingress of water. The material is resistant to freeze thaw cycles and exposure to harmful chemicals in comparison with RPF-free concrete making it have a longer service life and minimal maintenance.
- Microstructure: Incorporation of RPF narrows the inner structure of the concrete, hitting the number of interconnected pores and expanding the area of solid connection. Such modifications facilitate the corrosion resistance.
- Environmental Improvements: Life-cycle analysis shows that RPF-concrete has a major impact on carbon footprint, energy savings, and landfills, which are in line with the goals of circular-economy.
- Where and how to use it (Practicum): Implementation

involves maneuvering through technical and regulatory systems; but there is an emergence of RPF in building codes and the mainstream constructions. Field testing and digital monitoring will be done continuously to facilitate adoption.

Introduction of RPFs in concrete is a paradigm shift and one can see that waste management, materials science and green-building concepts are converged. The next emphasis is to be on monitoring performance in the field, the adaptation of the strategy depending on the conditions of the environment (e.g., marine or cold climates), and the implementation of intelligent monitoring systems to anticipate the problems and prevent them.

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