Incorporation of Recycled Plastic Aggregates in Concrete: Effects on Compressive Strength and Environmental Footprint

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Abstract — The escalating global demand for sustainable construction materials has spurred interest in incorporating recycled plastic aggregates into concrete to reduce environmental impact and address plastic waste. This study investigates the effects of substituting fine aggregates with recycled polyethylene terephthalate (PET) aggregates at 0%, 10%, and 20% replacement levels on concrete's compressive strength and environmental footprint. An experimental approach, following ASTM C39 standards, evaluates compressive strength at 7 and 28 days under varying curing temperatures (20°C, 30°C), with PET aggregates treated with silica fume to enhance bonding. A simplified life cycle assessment (LCA) quantifies CO2 emissions, focusing on material production and plastic recycling processes. Expected results indicate a 5-20% reduction in compressive strength but a 10-15% decrease in CO2 emissions at 20% replacement, supporting sustainability without compromising non-structural applications. The findings highlight the potential of recycled PET aggregates to balance mechanical performance and environmental benefits, contributing to greener construction practices. Limitations, such as long-term durability, are noted, with recommendations for future research into optimized processing and structural applicability.

Keywords: Recycled Plastic Aggregates, PET, Concrete, Compressive Strength, Environmental Footprint, Sustainability, Life Cycle Assessment, Construction Materials

I. Introduction

Concrete, a cornerstone of modern construction, is valued for its strength, durability, and versatility. Comprising cement, water, aggregates, and additives, it forms the backbone of infrastructure worldwide, with global production exceeding 4.1 billion metric tons annually (Gagg, 2014). However, the environmental toll of concrete production is significant, contributing approximately 8% of global CO2 emissions due to cement manufacturing and aggregate extraction (Andrew, 2018). As sustainability becomes a priority in civil engineering, researchers are exploring alternative materials to reduce concrete's environmental footprint while maintaining its mechanical properties. One promising approach is the incorporation of recycled plastic aggregates, derived from post-consumer plastic waste, as a partial replacement for traditional sand or gravel aggregates.

Historically, aggregates in concrete have been sourced from natural materials like river sand and crushed stone. However, the depletion of these resources, coupled with the global plastic waste crisis—estimated at 6.3 billion metric tons annually (Geyer et al., 2017)—has spurred interest in using recycled plastics. These materials, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), and polypropylene (PP), are abundant in waste streams and can be processed into aggregates. Current applications of recycled plastic aggregates include non-structural elements like pavements and lightweight concrete blocks, but their use in structural concrete remains limited due to concerns about reduced compressive strength and inconsistent performance (Saikia & de Brito, 2014).

The research problem lies in the trade-off between sustainability and performance. While recycled plastic aggregates offer environmental benefits, such as reduced landfill waste and lower resource extraction, studies report a decline in compressive strength—often by 10-30% compared to conventional concrete (Albano et al., 2009). Additionally, there is a lack of standardized data on the long-term durability and environmental impact of plastic aggregate concrete, particularly in structural applications. This gap hinders its adoption in building codes and industry practices. Furthermore, the life cycle assessment (LCA) of such concretes, including energy use and emissions during plastic processing, remains underexplored.

This paper aims to address these challenges by evaluating the effects of incorporating recycled PET aggregates in concrete on its compressive strength and environmental footprint. The objectives are to: (1) quantify the compressive strength of concrete with varying PET aggregate replacement levels (0%, 10%, 20%), (2) assess the environmental impact through a simplified LCA focusing on CO2 emissions, and (3) propose strategies to optimize the balance between mechanical performance and sustainability. By addressing these objectives, the study seeks to contribute to the development of sustainable concrete formulations suitable for structural applications.

II. Literature Review

The integration of recycled plastic aggregates into concrete has gained traction over the past decade, driven by the need to address plastic waste and reduce the environmental impact of construction. This section synthesizes findings from peer-reviewed studies (2015-2025) on the mechanical properties, environmental benefits, and innovations in plastic aggregate concrete, organized thematically around performance, sustainability, and processing techniques.

A. Mechanical Properties

Several studies have investigated the impact of recycled plastic aggregates on concrete's mechanical properties. Saikia and de Brito (2014) found that replacing 15% of fine aggregates with PET particles reduced compressive strength by 10-20%, attributed to the lower density and weaker bonding of plastics compared to sand. Similarly, Albano et al. (2009) reported a 30% strength reduction at 20% PET replacement, noting that irregular plastic particle shapes increased porosity. However, Gu and Ozbakkaloglu (2016)

observed that using treated HDPE aggregates improved workability and reduced strength loss to 10% at 15% replacement, suggesting surface treatment as a mitigation strategy. Thorneycroft et al. (2018) explored PP aggregates and found that optimizing particle size distribution could limit strength reduction to 5-10% at 10% replacement, highlighting the role of aggregate grading.

B. Environmental Impact

The environmental benefits of recycled plastic aggregates are well-documented. Choi et al. (2016) conducted an LCA, finding that replacing 20% of sand with PET aggregates reduced the carbon footprint of concrete by 12% due to lower aggregate extraction. However, the energy-intensive process of shredding and cleaning plastics partially offsets these gains (Yin et al., 2016). Ghernouti et al. (2018) noted that using locally sourced plastic waste could further reduce emissions by minimizing transportation. Conversely, Babafemi et al. (2018) cautioned that the long-term environmental impact, including microplastic leaching, remains understudied, particularly in structural applications.

C. Innovations in Processing

Recent innovations focus on improving the compatibility of plastic aggregates with concrete. Faraj et al. (2020) demonstrated that coating PET aggregates with silica fume enhanced interfacial bonding, reducing strength loss to 8% at 15% replacement. Similarly, Hannawi et al. (2016) explored thermal treatment of HDPE aggregates, improving their surface roughness and adhesion, which increased compressive strength by 5% compared to untreated plastics. Alqahtani et al. (2021) developed a synthetic lightweight aggregate from recycled plastic and fly ash, achieving comparable strength to conventional concrete at 10% replacement. These advancements suggest that processing techniques can mitigate mechanical drawbacks.

D. Research Gaps

Despite progress, contradictions persist in the literature. Some studies (e.g., Saikia & de Brito, 2014) report significant strength reductions, while others (e.g., Faraj et al., 2020) suggest minimal impact with proper treatment. The variability in plastic types, sizes, and processing methods complicates comparisons. Moreover, few studies conduct comprehensive LCAs that include plastic recycling processes, limiting understanding of net environmental benefits. Long-term durability, such as resistance to freeze-thaw cycles or chemical degradation, is also understudied, particularly for structural concrete.

This study addresses these gaps by systematically evaluating PET aggregates in concrete, focusing on compressive strength and environmental footprint. By standardizing aggregate size and incorporating surface treatment, the research aims to provide clearer insights into performance and sustainability.

Study	Plastic Type	Replacement (%)	Compressive Strength Impact	Environmental Impact
Saikia & de Brito (2014)	PET	15	-10.2	Reduced landfill waste
Albano et al. (2009)	PET	20	-30%	Not assessed
Gu & Ozbakkaloglu (2016)	HDPE	15	-10%	Lower extraction emissions
Thorneycroft et al. (2018)	PP	10	-5.1	Not assessed
Choi et al. (2016)	PET	20	Not reported	-12% CO2 emissions

Table 1: Summary of Key Studies on Recycled Plastic Aggregates in Concrete

III. Methodology

To investigate the effects of recycled PET aggregates on concrete's compressive strength and environmental footprint, an experimental study is proposed. This section outlines the materials, testing methods, sample preparation, and data collection procedures, justified by prior literature and practical considerations.

A. Materials

Concrete mixtures will be prepared with Type I Portland cement, natural sand (fine aggregate), crushed granite (coarse aggregate), and water. Recycled PET aggregates, sourced from post-consumer plastic bottles, will replace fine aggregates at 0% (control), 10%, and 20% by volume. PET aggregates will be shredded to a size range of 0.5-4 mm, consistent with Thorneycroft et al. (2018), to ensure uniform grading. To enhance bonding, PET particles will be coated with silica fume, as recommended by Faraj et al. (2020). The water-cement ratio will be fixed at 0.5, and a superplasticizer will be added to maintain workability.

B. Experimental Design

The study will test compressive strength per ASTM C39 standards using cylindrical specimens (150 mm diameter, 300 mm height). Three independent variables will be considered: PET replacement level (0%, 10%, 20%), curing time (7, 28 days), and curing temperature (20°C, 30°C). A total of 36 specimens (3 replacements × 2 curing times × 2 temperatures × 3 replicates) will be prepared to ensure statistical reliability.

C. Sample Preparation

Cement, sand, granite, and PET aggregates will be mixed in a rotary mixer for 5 minutes, followed by the addition of water and superplasticizer. PET aggregates will be pre-treated by soaking in a silica fume slurry for 24 hours and air-dried to enhance adhesion (Faraj et al., 2020). Mixtures will be cast into molds, vibrated to remove air voids, and cured in a controlled environment at the specified temperatures. After demolding, specimens will be stored in water tanks until testing.

D. Testing and Data Collection

Compressive strength will be measured using a universal testing machine with a loading rate of 0.25 MPa/s, as per

ASTM C39. Tests will be conducted at 7 and 28 days to assess early and standard strength development. For environmental impact, a simplified LCA will be performed, focusing on CO2 emissions from material production, plastic recycling, and transportation. Data will be sourced from literature (e.g., Choi et al., 2016) and the Ecoinvent database. Emissions will be calculated per cubic meter of concrete.

Equipment

- Rotary mixer: For uniform mixing of concrete constituents.
- Universal testing machine: For compressive strength testing (capacity: 2000 kN).
- Water tanks: For controlled curing at 20°C and 30°C.
- Sieve shaker: For grading PET aggregates.

E. Justification

The choice of PET aggregates aligns with their abundance in waste streams (Geyer et al., 2017). Silica fume treatment is selected based on Faraj et al. (2020) to mitigate strength loss. The replacement levels (10%, 20%) reflect practical ranges from prior studies (Saikia & de Brito, 2014). ASTM C39 ensures standardized, comparable results, while the LCA addresses the sustainability focus of the study. Limitations include the exclusion of long-term durability tests due to time constraints, which will be noted in the discussion.

IV. Expected Results and Discussion

Based on literature trends, the incorporation of recycled PET aggregates is expected to influence both compressive strength and environmental footprint. At 10% replacement, compressive strength is hypothesized to decrease by 5-10% compared to the control (0% PET), based on Thorneycroft et al. (2018) and Faraj et al. (2020), due to improved bonding from silica fume treatment. At 20% replacement, a 15-20% strength reduction is anticipated, consistent with Saikia and de Brito (2014), as higher plastic content increases porosity. Strength is expected to improve from 7 to 28 days due to continued cement hydration, with higher curing temperatures (30°C) potentially enhancing early strength gain by 5% (Gu & Ozbakkaloglu, 2016).

The LCA is expected to show a 10-15% reduction in CO2 emissions for 20% PET replacement, driven by reduced sand extraction and landfill diversion (Choi et al., 2016). However, emissions from plastic shredding and treatment may offset gains by 3-5% (Yin et al., 2016). The control mix is estimated to emit 400 kg CO2/m³, while the 20% PET mix may emit 340-360 kg CO2/m³.

PET Replacement (%)	Curing Time (days)	Temperature (°C)	Compressive Strength (MPa)
0 (Control)	28	20	40
10	28	20	37
20	28	20	33

Table 2: Expected Compressive Strength Results

These results could address the research gap by demonstrating that silica fume-treated PET aggregates achieve acceptable strength (above 30 MPa) for non-structural applications, such as pavements or low-load-bearing walls. The environmental benefits support sustainability goals, potentially aligning with green building standards like LEED. However, the strength reduction at 20% replacement may limit structural use unless further optimized.

A. Implications

The findings could encourage wider adoption of recycled plastic aggregates in construction, reducing reliance on natural resources and mitigating plastic waste. Cost savings from lower aggregate extraction (approximately $10-15/m³) may offset processing costs, though scalability depends on local recycling infrastructure. Regulatory compliance, such as meeting ASTM strength thresholds, remains a challenge for structural applications.

B. Limitations

The study's focus on short-term compressive strength excludes durability metrics like freeze-thaw resistance or creep, which are critical for long-term performance (Babafemi et al., 2018). The small sample size (36 specimens) may limit statistical power, and the LCA relies on secondary data, introducing uncertainty. Future studies could address these by expanding durability tests and using primary LCA data.

V. Conclusion

This study evaluates the incorporation of recycled PET aggregates in concrete, addressing their impact on compressive strength and environmental footprint. The proposed experiment tests 10% and 20% PET replacement levels, using silica fume treatment to enhance performance. Expected results indicate a 5-20% strength reduction, offset by a 10-15% decrease in CO2 emissions, supporting sustainability in construction. These findings address gaps in standardized data on plastic aggregate concrete, offering insights into balancing mechanical performance and environmental benefits.

The research has significant implications for sustainable construction, potentially reducing plastic waste and natural resource depletion. By achieving compressive strengths suitable for non-structural applications, the study paves the way for broader adoption of recycled materials. However, limitations in long-term durability data and structural applicability highlight the need for further research. Future studies should explore durability under environmental stressors, optimize plastic processing techniques, and conduct comprehensive LCAs to validate scalability. Integrating recycled plastic aggregates into building codes could further advance sustainable construction practices.

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