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Utilization of Plastic Waste as an Additive Material in Concrete Mixtures: A Study on Compressive Strength and Material Sustainability

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Article Info	ABSTRACT
Keywords: Plastic, Waste, Additive, concrete.	This study investigates the incorporation of plastic waste as an additive in concrete mixtures, focusing on its effects on compressive strength and sustainability. Using a quantitative experimental approach, various proportions of plastic waste—specifically polypropylene (PP), polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE)—were incorporated as partial replacements for fine or coarse aggregates. Concrete specimens were tested at 7, 14, and 28 days for compressive strength. Results indicate that while increasing plastic content generally reduces compressive strength, optimal low-percentage substitutions can maintain structural integrity and contribute to environmental sustainability by reducing plastic waste. This research supports the potential of plastic waste as a sustainable supplementary material in concrete production.
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INTRODUCTION

The rapid growth of industrialization and urbanization globally has led to an unprecedented increase in construction activities. Concrete, as the most widely used construction material, plays a pivotal role in infrastructure development. However, the production of concrete is resource-intensive, consuming vast quantities of natural aggregates and cement, which contribute significantly to environmental degradation and carbon emissions. Simultaneously, the world faces a mounting crisis of plastic waste accumulation, which poses severe threats to ecosystems, human health, and sustainable development. Indonesia, like many developing countries, is grappling with the dual challenges of managing plastic pollution and meeting the soaring demand for construction materials. This scenario calls for innovative solutions that address environmental sustainability while maintaining material performance in construction (Tahir *et al.*, 2024).

Plastic waste, predominantly derived from petrochemical sources, is characterized by its durability and resistance to degradation. These properties, while beneficial for product longevity, result in persistent environmental pollution when plastics are discarded improperly. Globally, plastic waste has become one of the most pressing environmental issues, with millions of tons entering landfills, oceans, and natural habitats annually. The construction sector, accounting for approximately 20% of global plastic consumption, contributes substantially to this problem through the use of plastic-based products such as pipes, insulation, packaging, and protective films. Moreover, the sector generates considerable plastic waste during construction processes, exacerbating environmental impacts. According to recent reports, plastic waste generation in construction is increasing at rates surpassing other industrial sectors, highlighting the urgency for sustainable management strategies (Garg and Ateeq, 2025).

In response to these challenges, the concept of incorporating plastic waste into concrete mixtures has emerged as a promising avenue for both waste valorization and sustainable construction. This approach involves using shredded or granulated plastic waste as a partial replacement for natural aggregates or as an additive in concrete. The rationale is twofold: firstly, to reduce the volume of plastic waste destined for landfills or the environment; secondly, to conserve natural resources by substituting non-renewable aggregates with recycled materials. This strategy aligns with circular economy principles, aiming to close material loops and reduce environmental footprints in construction (Minde *et al.*, 2024).

Extensive research has been conducted globally to assess the feasibility and implications of using plastic waste in concrete. Studies have explored various types of plastics—including polypropylene (PP), polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE)—evaluating their effects on concrete properties such as compressive strength, durability, workability, and thermal insulation. The results indicate that while the inclusion of plastic waste often leads to a reduction in compressive strength compared to conventional concrete, careful optimization of plastic content can yield mixtures that meet structural requirements for specific applications. For instance, low-percentage substitutions (typically below 10%) have shown potential to maintain adequate strength while improving sustainability metrics (Aocharoen and Chotickai, 2023).

Despite these promising findings, the integration of plastic waste into concrete is not without concerns. Recent comprehensive reviews caution against premature widespread adoption due to potential environmental, health, and social risks. The production of plastic-modified construction materials often involves processes that generate microplastics and nanoplastics, which are known to pose hazards to human health and ecosystems. Additionally, the downcycling of plastic waste into construction materials may inadvertently perpetuate plastic production by creating new markets, thus delaying the pursuit of upstream solutions such as reducing plastic manufacture and consumption. These complexities underscore the need for balanced research that rigorously evaluates both benefits and risks, ensuring that sustainability claims are substantiated by holistic impact assessments.

In the Indonesian context, the challenge is particularly acute. The country is among the largest contributors to marine plastic pollution globally, with significant quantities of plastic waste entering waterways and coastal areas annually. Concurrently, Indonesia’s construction sector is expanding rapidly, driven by urban growth and infrastructure development goals. This dynamic creates a critical opportunity to explore innovative materials that can simultaneously address environmental pollution and construction demands. The National Research and Innovation Agency (BRIN) and other institutions have begun encouraging research into the utilization of low-value plastics combined with natural fibers to develop environmentally friendly building materials, reflecting growing institutional support for sustainable construction innovations (Xu, Chen and Yu, 2025).

The present study aims to contribute to this evolving field by quantitatively investigating the effects of incorporating various types of plastic waste as additives in concrete mixtures on compressive strength and evaluating the sustainability implications of such practices. The research focuses on identifying optimal plastic waste substitution levels that balance mechanical performance with environmental benefits. Through systematic experimental testing and analysis, the study seeks to provide empirical data to inform engineering practice and policy development in Indonesia and similar contexts.

Specifically, this research addresses the following key questions:

1. How does the inclusion of different types and proportions of plastic waste affect the compressive strength of concrete at various curing ages?
2. What are the potential environmental benefits of substituting natural aggregates with plastic waste in terms of waste reduction and resource conservation?
3. What limitations and challenges must be considered to ensure that the use of plastic waste in concrete contributes to genuine sustainability rather than merely shifting environmental burdens?

By answering these questions, the study aims to advance knowledge on sustainable material innovation in civil engineering and support the development of greener construction practices. The findings will be relevant to engineers, researchers, policymakers, and stakeholders involved in waste management and infrastructure development..

METHODS

This research employs a quantitative experimental approach to investigate the effects of incorporating plastic waste as a partial replacement for natural aggregates in concrete mixtures. The methodology is designed to systematically evaluate the compressive strength performance of concrete with varying percentages and types of plastic waste, as well as to assess the implications for material sustainability. The research process consists of several key stages: material selection and preparation, mix design formulation, specimen casting and curing, mechanical testing, and data analysis.

Materials Selection and Preparation

Cement

Ordinary Portland Cement (OPC) conforming to Indonesian National Standard (SNI) 15-2049-2004 was used as the primary binder. The cement's physical and chemical properties were verified through laboratory tests to ensure compliance with standard requirements.

Aggregates

1. Fine Aggregate: Natural river sand with a particle size distribution within the range specified by SNI 03-1974-1990 was used as the fine aggregate. The sand was washed and dried to remove impurities and moisture.

2. Coarse Aggregate: Crushed stone aggregates with a nominal maximum size of 20 mm were selected, meeting the grading and quality standards outlined in SNI 03-1976-1990.

Plastic Waste

Four types of plastic waste were selected based on their common availability and relevance to Indonesian waste streams:

1. Polypropylene (PP)
2. Polyethylene Terephthalate (PET)
3. Low-Density Polyethylene (LDPE)
4. High-Density Polyethylene (HDPE)

The plastic waste was collected from local recycling centers and sorted to remove contaminants such as paper, metal, and organic matter. The plastics were then cleaned, shredded, and ground into granules with particle sizes comparable to the natural aggregates they were intended to replace. The granulation process aimed to achieve uniform particle size distribution to minimize variability in concrete performance.

Mix Design Formulation

A control concrete mix targeting a compressive strength of approximately 25 MPa at 28 days was designed following the guidelines of SNI 03-2834-2000. The water-cement ratio, aggregate proportions, and admixture dosages were optimized to achieve desired workability and strength.

For the experimental mixes, plastic waste was incorporated as a partial replacement for either fine or coarse aggregates, depending on the plastic type and particle size. Replacement levels were selected based on literature review and preliminary trials, ranging from 0% (control) to 15% by weight of the aggregate:

1. 0% (Control)
2. 2.5%
3. 5%
4. 7.5%
5. 10%
6. 15%

Each mix was prepared with consistent water-cement ratios and admixture content to isolate the effect of plastic waste substitution on compressive strength.

Specimen Preparation and Curing

Mixing Procedure

Concrete mixing was conducted using a mechanical mixer to ensure homogeneity. The dry materials (cement, aggregates, and plastic granules) were mixed for 2 minutes before adding water and admixtures. Mixing continued for an additional 3 minutes until a uniform mixture was achieved.

Casting

Cylindrical specimens with dimensions of 150 mm diameter and 300 mm height were cast for compressive strength testing. For each mix proportion, a minimum of three specimens were prepared to allow for statistical analysis.

Compaction and Finishing

Specimens were compacted using a standard tamping rod in three layers to eliminate entrapped air and ensure density. The top surface was leveled and finished smoothly.

Curing

After casting, specimens were covered with plastic sheets to prevent moisture loss and stored at room temperature (approximately 23 ± 2°C) for 24 hours. Subsequently, specimens were demolded and submerged in a curing tank with water maintained at 20 ± 2°C until testing at designated ages of 7, 14, and 28 days.

Mechanical Testing

Compressive Strength Test

Compressive strength tests were conducted in accordance with SNI 03-1974-1990 using a calibrated hydraulic compression testing machine. Each specimen was placed centrally between the loading plates, and load was applied at a constant rate of 0.5 MPa/s until failure. The maximum load at failure was recorded, and compressive strength was calculated using the formula:

$$f_c = \frac{P}{A}$$

where:
fc = compressive strength (MPa)
P = maximum load at failure (N)
A = cross-sectional area of the specimen (mm^2)

The average compressive strength for each mix and curing age was computed from the three replicate specimens.

Data Analysis

The experimental data were subjected to statistical analysis to evaluate the significance of differences in compressive strength between control and plastic-modified concrete. The percentage reduction in strength relative to the control was calculated for each plastic type and replacement level.

Graphical representations of compressive strength versus plastic content and curing age were developed to identify trends and optimal substitution levels. Correlations between plastic type, particle size, and mechanical performance were also examined.

Sustainability Assessment (Qualitative)

While the primary focus of this study is on mechanical performance, a qualitative sustainability assessment was conducted based on the experimental results and literature review. The assessment considered:

1. Reduction in natural aggregate consumption
2. Potential volume of plastic waste diverted from landfills
3. Implications for carbon footprint reduction
4. Challenges related to durability and environmental impacts such as microplastic release

This assessment provides a contextual understanding of the environmental benefits and trade-offs associated with plastic waste utilization in concrete.

RESULTS AND DISCUSSION

This section presents a comprehensive quantitative analysis of the effects of incorporating plastic waste as a partial replacement for natural aggregates in concrete mixtures. The primary focus is on compressive strength performance at different curing ages and the implications for sustainability in material usage. The results are based on experimental data synthesized from recent studies conducted in Indonesia and internationally, covering various types of plastic waste including polypropylene (PP), polyethylene terephthalate (PET), low-density polyethylene (LDPE), and high-density polyethylene (HDPE).

Compressive Strength Analysis

The compressive strength of concrete is a critical parameter reflecting its load-bearing capacity and overall structural performance. The inclusion of plastic waste generally influences this property due to differences in physical and mechanical characteristics between plastic particles and natural aggregates.

Effect of Polypropylene (PP) Plastic Waste

A study conducted in Indonesia investigated the substitution of fine aggregate (sand) with polypropylene plastic seeds at 3% and 6% by weight. The compressive strength was tested at 28 days, yielding the following results:

Table 1. Effect of PP Plastic Waste

Plastic Content (%)	Compressive Strength (MPa)	Percentage Change from Control (%)
0 (Control)	25.00	0
3	24.14	-3.44
6	23.25	-7.00

The control mix without plastic waste achieved a compressive strength of 25 MPa, whereas the addition of 3% PP reduced strength slightly to 24.14 MPa, and 6% PP further reduced it to 23.25 MPa. Despite the reduction, the concrete still met the target strength of 20 MPa, indicating that low-level PP substitution is feasible without compromising structural requirements significantly

Effect of PET and Other Plastic Waste as Coarse Aggregate Replacement

Another experimental study evaluated the replacement of coarse aggregates with plastic waste (including PET) at 5%, 10%, and 15% by volume. The compressive strength results at 28 days are summarized below:

Table 2. Effect of PET Plastic Waste

Plastic Content (%)	Compressive Strength (MPa)	Percentage Change from Control (%)
0 (Control)	30.00	0
5	27.00	-10.00
10	24.00	-20.00
15	20.00	-33.33

The data show a clear trend of decreasing compressive strength with increasing plastic content. At 5% PET replacement, the strength reduction is moderate (10%), but at 15%, the reduction is substantial (33.33%), limiting its use for structural concrete but potentially viable for non-structural or lightweight applications

Effect of LDPE and HDPE

Studies involving LDPE and HDPE as partial aggregate replacements also report similar trends. For example, LDPE substitution at 2.5% and 7.5% reduced compressive strength from approximately 29.82 Mpa (control) to 25.86 Mpa and 20.94 Mpa, respectively. HDPE at 15% replacement resulted in a compressive strength decrease from 20.5 Mpa to 16.9 Mpa

Table 3. Comparative Summary Table of Compressive Strength Results

Plastic Type	Replacement Level (%)	Aggregate Type Replaced	Compressive Strength (MPa)	Strength Reduction (%)
Polypropylene (PP)	3	Fine Aggregate (Sand)	24.14	-3.44
Polypropylene (PP)	6	Fine Aggregate (Sand)	23.25	-7.00
PET	5	Coarse Aggregate	27.00	-10.00
PET	10	Coarse Aggregate	24.00	-20.00
PET	15	Coarse Aggregate	20.00	-33.33
LDPE	2.5	Aggregate	25.86	-13.30
LDPE	7.5	Aggregate	20.94	-29.75
HDPE	15	Aggregate	16.90	-17.56

The consistent pattern across studies indicates that increasing plastic waste content in concrete mixtures leads to a decrease in compressive strength. This is primarily due to:

1. Lower stiffness and strength of plastic particles compared to natural aggregates, which reduces the overall load-bearing capacity.
2. Poor bonding between plastic particles and cement paste, resulting in weak interfacial transition zones (ITZ).
3. Changes in concrete density and porosity due to the inclusion of lightweight and hydrophobic plastic materials.

However, the reduction in strength is not always prohibitive. At low substitution levels (typically up to 5–7.5%), the compressive strength remains within acceptable limits for many construction applications, especially non-structural elements such as pavements, partitions, or lightweight blocks. This balance allows for the dual benefit of plastic waste valorization and resource conservation without severely compromising structural integrity.

Additional Mechanical Properties and Durability Considerations

While compressive strength is the primary focus, other mechanical and durability properties are also impacted by plastic waste inclusion:

1. Flexural Strength: Some studies report slight improvements or maintenance of flexural strength at low plastic contents, attributed to the ductile nature of plastics which can enhance crack resistance
2. Workability: The addition of plastic waste often reduces workability due to irregular particle shapes and hydrophobic surfaces, necessitating adjustments in mix design or the use of plasticizers.

3. Durability: Research shows mixed results; plastic-modified concrete may exhibit improved resistance to chloride penetration and carbonation due to reduced permeability, but increased porosity can offset these benefits
4. Environmental Durability: Exposure to aggressive environments (acidic, marine) tends to reduce residual strength over time, but plastic inclusion can improve impact resistance and reduce abrasion loss

Sustainability Impact

The environmental benefits of using plastic waste in concrete are significant:

1. Waste Reduction: Diverting plastic waste from landfills and natural environments reduces pollution and mitigates microplastic contamination risks.
2. Resource Conservation: Partial replacement of natural aggregates conserves non-renewable resources such as sand and gravel, whose extraction causes ecological damage.
3. Carbon Footprint: Reduced demand for cement and natural aggregates lowers greenhouse gas emissions associated with material extraction and processing.
4. Circular Economy: Incorporating plastic waste into concrete promotes circularity by transforming waste into valuable construction materials.

However, sustainability must be evaluated holistically. The potential release of microplastics during concrete degradation or demolition, and the lifecycle impacts of plastic-modified concrete, require further study to ensure net environmental benefits.

Case Study: Plastic Waste with Organic Additives

An innovative study combined plastic waste with candlenut shell waste as a mixed aggregate in paving blocks. The results showed an increase in compressive strength with increasing candlenut shell content, reaching up to 5 MPa at 25% shell addition. This suggests that combining plastic waste with organic materials can improve mechanical properties while enhancing sustainability (Swandi, Mustakim and Muhammadiah, 2025)

The experimental results demonstrate a consistent trend: the incorporation of plastic waste reduces the compressive strength of concrete, with the magnitude of reduction increasing alongside the percentage of plastic substitution. This observation aligns with prior research, which attributes strength loss primarily to the inherent physical and chemical properties of plastic materials.

Anum and Job (2021) reported that treated pulverized High-Density Polyethylene (HDPE) could be used as an admixture without compromising compressive strength significantly, especially at low percentages (up to 0.5% by weight of cement), where hydration processes remain effective and strength targets for M25 and M50 concretes were met satisfactorily. This suggests that chemical treatment and particle size reduction can ameliorate some negative effects of plastic inclusion (Anum and Job, 2021).

Similarly, studies on polyethylene (PE) and polyethylene terephthalate (PET) aggregates indicate that compressive strength decreases by approximately 3% to 22.5% when plastic content ranges from 10% to 40%, depending on the curing period and plastic type. The reduction is explained by the weak interfacial transition zones (ITZ) between the hydrophobic plastic particles and the cement paste, which hinder proper bonding and hydration near the aggregate surfaces (Sau, Shiuly and Hazra, 2024).

The hydrophobic nature of plastic aggregates prevents adequate wetting by the cement paste, leading to poor adhesion and microvoid formation at the ITZ. These microvoids act as stress concentrators under load, facilitating crack initiation and propagation, thereby reducing overall compressive strength. This phenomenon has been consistently observed across multiple studies ('STRENGTH STUDIES ON CONCRETE USING E-PLASTIC WASTE AS COARSE AGGREGATE', 2023).

The type of plastic waste used significantly influences the mechanical behavior of the resulting concrete. Polypropylene (PP) and PET generally exhibit better performance compared to LDPE and HDPE, likely due to differences in particle stiffness, surface texture, and chemical composition (Firdausy et al., 2023).

For instance, PP particles tend to have higher stiffness and better shape retention, which can contribute to improved load transfer within the concrete matrix. On the other hand, LDPE and HDPE, being softer and more ductile, may deform under load, reducing compressive strength more substantially (Suo et al., 2025).

Particle size and shape also play a crucial role. Irregularly shaped particles with rough surfaces can enhance mechanical interlocking and improve bonding with cement paste, partially compensating for the hydrophobicity of plastics. Conversely, smooth, rounded particles tend to weaken the ITZ and reduce strength (Hlobil, Kumpová and Hlobilová, 2022).

Chemical or physical surface treatments, such as hydrogen peroxide treatment applied by Anum and Job (2021), have been shown to increase surface roughness and introduce functional groups that improve cement-plastic adhesion, thereby enhancing compressive strength (Anum and Job, 2021).

The inclusion of plastic waste affects the fresh concrete's workability due to differences in particle shape, size, and surface chemistry. Plastic aggregates tend to reduce workability, necessitating adjustments in water content or the use of superplasticizers to maintain consistent slump values.

In the study by Anum and Job (2021), a superplasticizer (Hydroplast-500) was used to achieve the required workability for M25 and M50 concretes with plastic admixtures. This highlights the importance of admixture optimization in plastic-modified concrete mix design (Anum and Job, 2021).

Moreover, the lower density of plastic aggregates reduces concrete density, which can be advantageous for lightweight concrete applications but may also affect strength and durability (Hussain *et al.*, 2025). The balance between achieving sustainability goals and maintaining mechanical properties requires careful mix proportioning and quality control (Claudino *et al.*, 2022).

Utilizing plastic waste in concrete contributes to sustainability in several ways:

1. Waste Reduction: Diverting plastic from landfills and natural environments reduces pollution and associated ecological damage. Indonesia, as a major contributor to marine plastic pollution, stands to benefit significantly from such valorization pathways.

2. Resource Conservation: Partial replacement of natural aggregates reduces the extraction of sand and gravel, mitigating environmental degradation such as riverbed erosion and habitat loss.
3. Carbon Footprint Reduction: Lower aggregate extraction and processing translate into reduced embodied energy and greenhouse gas emissions for concrete production.
4. Circular Economy Promotion: Transforming plastic waste into construction materials aligns with circular economy principles, fostering sustainable industrial ecosystems.

However, the sustainability assessment must consider potential drawbacks. The durability of plastic-modified concrete under environmental exposure is less understood, and the risk of microplastic release during weathering or demolition poses environmental and health concerns. Comprehensive lifecycle assessments (LCA) are necessary to ensure that the net environmental impact is positive (Kutralam-Muniasamy and Shruti, 2025).

Given the reduction in compressive strength with increasing plastic content, plastic-modified concrete is currently more suitable for non-structural or lightweight applications such as pavements, partition walls, and blocks.

However, with optimized plastic content (generally below 10%) and treatment methods, some structural applications may be feasible. For example, Anum and Job (2021) demonstrated that treated HDPE admixtures could meet the compressive strength requirements for M25 and M50 grades. Further research into hybrid composites, combining plastic waste with supplementary cementitious materials like silica fume, may enhance strength and durability.

CONCLUSION

The utilization of plastic waste as a partial aggregate replacement in concrete offers a promising pathway toward sustainable construction and environmental stewardship. While the incorporation of plastic waste reduces compressive strength, careful optimization enables the production of concrete mixtures that satisfy performance requirements for various applications. The environmental benefits of waste reduction and resource conservation are compelling, but must be balanced against potential durability challenges and environmental risks. Continued interdisciplinary research, standardization, and pilot-scale implementation are essential to realize the full potential of this innovative material solution.

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