Development and Analysis of Eco-Friendly Composite Materials for Low-Load Structural Applications Using Plastic Waste and PET Bottles

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Abstract

The twenty-first century has witnessed an unprecedented escalation in plastic production. This creates a pressing environmental challenge globally. Currently over 400 million tons of plastic are produced worldwide annually. Less than 9 percent is properly recycled. In Kenya solid waste generation is approximately 1 million tons annually. Plastics constitute up to 20 percent in major urban centres like Nairobi and Mombasa. Successful initiatives include the 2017 plastic bag ban. Single-use items like PET bottles remain pervasive in the informal waste sector. This exacerbates leakage into waterways and soils.

The rapid accumulation of plastic waste and the parallel depletion of natural river sand for construction present dual environmental challenges in Kenya. This study investigates the development of eco-friendly composite materials. These materials are for the production of interlocking paving blocks, partition blocks, and landscaping tiles. Recycled Polyethylene Terephthalate (PET) waste replaces fine aggregates. Shredded PET bottles replace river sand at volumetric mass equivalent levels of 0, 5, 10, 15, and 20 percent in a standard cementitious mix. Physical and mechanical properties include workability, density, water absorption, and compressive strength. We evaluated these per standard BS EN and ASTM protocols. Results indicate a systematic reduction in density and workability with increasing PET content. Compressive strength decreases progressively due to stiffness incompatibility and the hydrophobic nature of the interfacial transition zone. The 5 percent PET replacement mix achieved a 28-day compressive strength of 14.49 MPa. This formulation satisfies the requirements for pedestrian walkways, cycle paths, and non-load-bearing applications. It successfully demonstrates the technical viability of diverting municipal plastic waste into sustainable urban infrastructure.

Keywords: Polyethylene Terephthalate (PET), Composite Materials, Eco-Friendly Concrete, Interlocking Paving Blocks, Circular Economy, Compressive Strength.

1 Introduction

Rapid urbanization in Kenya triggers an explosive demand for precast concrete products. These include interlocking paving blocks and non-load-bearing partition blocks. Conventional production relies heavily on natural river sand. Intense unregulated mining of sand from major river basins causes severe environmental consequences. These include lowered water tables and the destruction of riparian ecosystems. Kenya faces a dual crisis. The over -exploitation of natural aggregates causes scarcity and environmental destruction. Uncontrolled plastic waste accumulation worsens the situation.

This research addresses this intersection by developing and rigorously characterizing an optimized eco-composite for paving blocks, partition blocks, and landscaping tiles. Postconsumer PET bottles serve as a partial replacement for natural fine aggregates. This study minimizes raw material consumption while delivering solid structural performance compliant with Kenyan construction standards.

2 Theoretical Framework and Literature

Integrating recycled plastics into civil engineering applications has evolved. Initial research focused on 100 percent plastic binders melted at high temperatures. These exhibited zero water absorption and high impact resistance. They suffered from low elastic modulus and massive thermal expansion.

Subsequent research shifted toward using shredded plastic as a partial replacement for mineral aggregates in traditional Ordinary Portland Cement matrices. Studies demonstrated replacing fine aggregate with PET flakes reduces compressive strength linearly. The Interfacial Transition Zone governs this reduction. Natural aggregates are rigid. Plastics are flexible. Under load the plastic deforms faster than the surrounding cement. This causes debonding. The hydrophobicity of PET prevents capillary suction of the cement paste. This creates local voids with high water to-cement ratios. These act as stress concentrators.

Current literature lacks systematic optimization using real-world unrefined municipal waste streams targeting the specific geometry and performance requirements of East African standards. This study fills this gap by utilizing locally collected unsorted PET waste for low load applications.

3 Materials and Methodology

3.1 Materials

The primary binding agent utilized was Ordinary Portland Cement of grade 32.5N. Natural River sand sieved to remove particles larger than 4.75 mm served as the fine aggregate.

Waste PET bottles were sourced from local dumpsites in Eldoret. The bottles were manually sorted, washed, air-dried, and mechanically shredded into flakes ranging from 2 to 4 mm. The specific gravity of the PET flakes was measured at 1.38. This compares to 2.65 for the natural river sand. The bulk density is 350 kg/m^3. Clean tap water meeting BS EN 1008 standards was used for mixing and curing.

3.2 Mix Design and Preparation

A mass-based replacement method was employed. Specific percentages of the fine aggregate mass were replaced by PET flakes. Five mix designs were formulated. These include a Control mix with 0 percent PET and four experimental mixes with 5, 10, 15, and 20 percent PET replacement.

The dry constituents were homogenized in a pan mixer for 3 minutes. Water was introduced gradually to achieve desired workability. Fresh concrete was subjected to the slump test prior to casting into standard 150 mm steel cube moulds. Compaction was achieved using a vibrating table at 3000 vibrations per minute for 60 seconds. Specimens were demoulded after 24 hours and submerged in a water curing tank at $20^{\circ}C$ until the designated testing age.

3.3 Testing Protocols

Workability was evaluated via the standard slump cone test per BS EN 12350-2 immediately after mixing. Density of hardened concrete was measured at 28 days via dimensional and mass measurement per BS EN 12390-7. Water Absorption was tested in accordance with ASTM C642 via oven drying and 24-hour water immersion. Compressive Strength was determined using a Digital Universal Testing Machine per BS EN 12390-3 at 7, 14, and 28 days.

4 Results and Discussion

4.1 Physical Properties

4.1.1 Workability

The workability of fresh concrete influences placement. Results revealed a clear inverse relationship between PET content and workability. The control mix achieved a slump of 90 mm. As PET replacement increased to 20 percent the slump dropped to 40 mm. This represents a 55.6 percent reduction. This is attributed to the flaky irregular shape of the shredded PET. It increases inter-particle friction. The hydrophobic nature of the plastic prevents the formation of a stable lubricating water film. All mixes remained within the acceptable BS EN 12350-2 workable range for paving applications.

Table 1: Physical Properties of PET-Modified Concrete

Mix ID	PET (%)	Slump (mm)	Density (kg/m^3)	Water Abs. (%)
Control	0	90	2415	4.2
Mix A	5	78	2310	4.8
Mix B	10	65	2240	5.3
Mix C2	15	52	2160	5.9
Mix D	20	40	2090	6.5

4.1.2 Density and Unit Weight

Density testing demonstrated a consistent linear reduction with increasing PET content. The control mix exhibited a normal-weight density of 2415 kg/m^3. At 20 percent replacement the density decreased to 2090 kg/m^3. This represents a 13.4 percent mass reduction. The specific gravity of PET is approximately half of sand. A mass-for-mass replacement increases the volume of lightweight inclusions. Mixes with 15 and 20 percent PET fall into the semi lightweight classification. They offer structural dead-load reduction and transport economics.

4.1.3 Water Absorption

Water absorption increased progressively from 4.2 percent to 6.5 percent. The poor bonding at the PET-cement interface generates micro-voids. This facilitates water ingress. The inherent zero-absorption characteristic of the PET particles mitigates porosity increases. All experimental mixes successfully complied with the KS 2769:2018 maximum allowable limit of 7 percent.

4.2 Mechanical Properties

Compressive strength testing served as the primary indicator of structural viability. Table 2 outlines the strength development across 7, 14, and 28 days of curing.

Table 2: Compressive Strength Development

Mix ID	PET (%)	7-Day (MPa)	14-Day	28-Day
Control	0	16.22	21.24	25.00
Mix A	5	9.42	12.31	14.49
Mix B	10	6.22	8.13	9.54
Mix C2	15	4.89	6.40	7.50
Mix D	20	3.41	4.40	5.19

The control mix achieved a 28-day strength of 25.00 MPa. This conforms to the KS 2769 Class 25 standard for residential driveways and light vehicle traffic. The introduction of PET resulted in a linear decrease in compressive capacity. Mix A retained approximately 58 percent of the control strength. It achieved 14.49 MPa. Mix D saw a 79.2 percent strength loss. It dropped to 5.19 MPa.

4.3 Discussion on Strength Degradation

The systematic strength reduction is directly linked to the degradation of the Interfacial Transition Zone. As a hydrophobic polymer PET repels the hydration water of the cement paste. This results in locally elevated water-to cement ratios at the particle boundaries. This yields fragile $Ca(OH)_2$ crystals rather than robust calcium silicate hydrate gels. Under axial load the ductile PET particles deform. They pull away from the rigid cement matrix and create macroscopic fissures. These fissures precipitate shear failure.

The relative strength gain trajectory remained consistent across all mixes. The average gain is 52 to 54 percent between day 7 and day 28. This indicates the fundamental cement hydration chemistry remains uninterrupted by the chemically inert PET inclusions. The mechanical performance is purely limited by internal physical discontinuities.

The current experimental phase observes a severe 79.2 percent strength loss at a 20 percent PET replacement level. This limits the higher-load structural viability of the material. The study identifies stiffness incompatibility and ITZ hydrophobicity as the primary causes. We did not test mitigation strategies within this phase. Mechanical testing stopped at 28 days. Long-term durability and weather resistance remain unaddressed in the current scope.

4.4 Application Suitability Analysis

Benchmarking the results against the Kenya Standard KS 2769:2018 identifies appropriate application domains for these materials. The control mix qualifies for light vehicular traffic. The 5 percent PET composite borders on the 15 MPa threshold required for Class 15 pedestrian applications. Mix A is designated as the optimal formulation for non-traffic environments. These include pedestrian walkways, garden paths, public plazas, and internal non-load-bearing partition walls. Mixes exceeding 10 percent replacement are relegated to decorative landscaping features. Structural integrity is not a design constraint here.

5 Conclusions and Future Work

This study systematically investigated the incorporation of unrefined PET waste into cementitious composites. This addresses Kenya concurrent plastic pollution and aggregate scarcity crises. The key findings and future recommendations are listed below.

1. Integrating shredded PET waste reduces the density of precast concrete by up to 13.4 percent. This offers logistical and structural dead-load benefits.

2. Workability decreases linearly with plastic content due to high inter-particle friction and hydrophobicity. Standard vibration equipment remains sufficient for compaction up to 20 percent replacement.

3. Water absorption increases with higher PET volume due to ITZ micro-voids. All tested mixes remained below the 7 percent maximum threshold specified by KS 2769:2018.

4. Compressive strength drops due to the weak ITZ and stiffness incompatibility between PET and cement. The 5 percent mass replacement mix is the structural optimum. It achieves 14.49 MPa at 28 days.

5. The 5 percent PET composite is feasible for commercial deployment in Class 15 applications like pedestrian walkways. A production rate of 100 m^3 per month sequesters approximately 60 tonnes of plastic waste annually. This drives direct contributions toward UN Sustainable Development Goals 9, 11, and 12.

6. Future research phases must actively address the weaknesses found at the particle boundary layer. They should implement and test chemical surface treatments on the recycled PET flakes. By Applying sodium hydroxide etching or silane coupling agents, this will improve adhesion at the ITZ and mitigate compressive strength loss.

7. Future Researchers must conduct extended durability testing beyond the initial 28-day curing period. They need to assess material performance under continuous environmental exposure and physical wear.

8. Future researchers must explore alternative mix designs with supplementary cementitious materials. This will offset the mechanical penalties introduced by shredded plastic aggregates.

6 References

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