ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.616

Recycled HDPE–Sand Composite Blocks: Strength and Moisture Resistance

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Abstract*– Portland cement production is a major contributor to global carbon dioxide emissions, while plastic waste particularly high-density polyethylene (HDPE) continues to accumulate in landfills and natural environments, especially in Small Island Developing States (SIDS). This study investigates the feasibility of using recycled HDPE as a cement-free binding phase in sand-based composite blocks intended for non-structural construction applications. HDPE–sand composites were produced at plastic-to-sand mass ratios of 2:8, 3:7, and 4:6 and compared against conventional cement–sand control specimens. Mechanical performance was evaluated using compressive strength, point load resistance, and a comparative drop-energy impact resistance test, while durability-related behavior was assessed through water absorption, apparent porosity, short-term pH immersion, and exploratory load-bearing thermal exposure. The results indicate that HDPE–sand composites can achieve compressive strengths within ranges suitable for non-structural masonry and paving units, with the 3:7 HDPE–sand ratio providing the most favorable balance between strength, ductility, and durability. At 28 days, the optimal mix achieved compressive strengths of approximately 18 MPa, satisfying ASTM C90 and regional block standards. All HDPE-based composites exhibited significantly lower water absorption (≤0.5%) and higher impact energy absorption than cement–sand controls due to the hydrophobic and viscoelastic nature of the polymer binder. Thermal exposure testing highlighted a clear service-temperature limitation for unmodified HDPE composites, defining their current application envelope. Overall, recycled HDPE–sand composites demonstrate strong potential for paving blocks, pedestrian infrastructure, and partition elements, offering a practical pathway for plastic waste valorization and reduced reliance on cement-based materials in tropical and resource-constrained environments.

Keywords*-- Cement-free composites; high-density polyethylene (HDPE); non-structural masonry units; plastic–sand composites; recycled plastics; sustainable construction materials.

I. INTRODUCTION (HEADING 1)

Portland cement is one of the most widely used construction materials worldwide; however, its production is associated with substantial environmental impacts. The cement industry contributes approximately 7–8% of global anthropogenic carbon dioxide (CO_2) emissions, primarily due to limestone calcination and the combustion of fossil fuels during clinker production [1]–[3]. On average, the manufacture of one ton of ordinary Portland cement releases between 0.80 and 0.95 tons of CO_2, depending on production efficiency and fuel source [2]. While the use of supplementary cementitious materials (SCMs) such as fly ash, slag, and natural pozzolans has been shown to reduce embodied carbon, these materials are often constrained by regional availability, supply chain limitations, and competing industrial demands [4]. As a result, increasing attention has been directed toward alternative binder systems that can reduce or eliminate reliance on clinker-based cement, particularly for non-structural construction applications.

At the same time, plastic waste has emerged as a critical global environmental challenge due to its persistence, low biodegradability, and rapidly increasing production rates. Since the mid-20th century, more than 6.3 billion tons of plastic waste have been generated globally, with a large proportion accumulating in landfills and natural ecosystems [5]. High-density polyethylene (HDPE) is among the most commonly produced thermoplastics and is widely used in packaging, containers, and piping due to its chemical resistance, durability, and relatively high melting temperature [6]. Despite its recyclability, a significant fraction of post-consumer HDPE remains underutilized, particularly in Small Island Developing States (SIDS), where recycling infrastructure and end-use markets are limited [7]–[9].

From a materials engineering perspective, HDPE exhibits properties that make it attractive for construction-related applications, including low water permeability, high impact resistance, and ductile deformation behavior [6], [10]. Unlike thermosetting polymers, HDPE can be repeatedly melted and reprocessed, enabling its use as a binding phase when combined with granular materials such as sand. The hydrophobic nature of HDPE further suggests that composites formed with mineral aggregates may exhibit improved resistance to moisture ingress compared to conventional cement-based materials, which is particularly relevant for tropical and high-rainfall environments.

Existing research on plastic-based construction materials generally follows two main approaches: (i) partial replacement of fine or coarse aggregates with plastic in cementitious composites, and (ii) plastic–sand composites in which molten plastic acts as the primary binder. Studies adopting the first approach have shown that limited plastic replacement can improve ductility and reduce density, although excessive plastic content often results in reduced compressive strength due to weak interfacial bonding and poor stress transfer [11]–[13]. In contrast, plastic–sand composites eliminate cement entirely and rely on the thermoplastic phase to bind granular particles. Several studies have reported compressive strength values comparable to those of conventional paving blocks and non-structural masonry units, alongside significantly reduced water absorption and enhanced impact resistance [14]–[18].

Despite these promising outcomes, the reported performance of plastic–sand composites varies widely depending on plastic type, mix ratio, processing temperature, mixing method, compaction technique, and aggregate grading. Furthermore, many studies focus primarily on compressive strength, with comparatively limited evaluation of durability-related properties such as water absorption, porosity, impact resistance, and thermal sensitivity. The latter is particularly important, as thermoplastic binders are inherently sensitive to elevated temperatures. In addition, relatively few experimental studies explicitly address conditions relevant to tropical and SIDS contexts, where high ambient temperatures, moisture exposure, and waste-management challenges coexist [9], [15].

In response to these gaps, this work investigates the use of recycled HDPE as a primary binder in sand-based composite construction blocks intended for non-structural applications. The study evaluates HDPE–sand composites produced at different plastic-to-sand ratios and compares their mechanical and durability-related performance with conventional cement–sand control specimens. The specific objectives of the study are to (i) assess the feasibility of recycled HDPE as a cement-free binder for sand-based construction units, (ii) identify an optimal HDPE–sand ratio based on compressive strength, water absorption, and impact resistance, and (iii) define service-temperature limitations through exploratory thermal exposure testing. By providing experimentally derived performance data using a practical fabrication approach, this study contributes to the development of low-cement, waste-derived construction materials that support plastic waste valorization and sustainable infrastructure development in tropical and resource-constrained regions.

II. Material And Methodology

A. Materials

Post-consumer high-density polyethylene (HDPE) waste was collected from local waste streams and manually sorted to remove visible contaminants. The plastic consisted primarily of packaging materials and containers, reflecting commonly available HDPE waste in Small Island Developing State (SIDS) contexts. Prior to use, the HDPE was washed, air-dried, and shredded. No chemical additives, compatibilizers, or surface treatments were applied to reflect a low-cost, practical, and scalable processing approach suitable for resource-constrained environments [14], [15]. The physical form of the shredded HDPE and the processed sand used in this study are illustrated in Fig. 1. Locally sourced sharp sand was used as the granular phase. To minimize variability and ensure consistency across all mixtures, the sand was oven-dried and sieved to pass a No. 50 (300 μm) sieve, following approaches adopted in previous plastic–sand composite studies [14], [17]. Ordinary Portland cement (OPC) was used exclusively for the preparation of cement–sand control specimens, providing a conventional baseline for comparative assessment of mechanical and durability-related performance. All materials and specimen preparation were conducted under controlled laboratory conditions at an ambient temperature of approximately 25–27 °C.

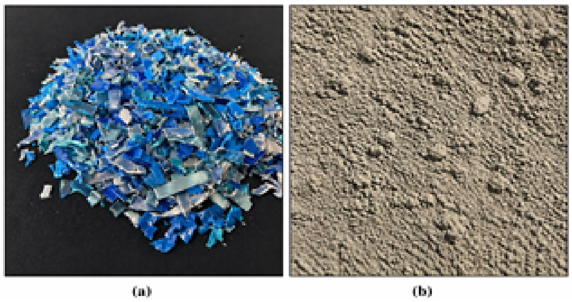

Fig. 1 Materials (a) Shredded HPDE waste (b) sand.

B. Mix Proportions and Conditioning

HDPE–sand composites were prepared at plastic-to-sand mass ratios of 2:8, 3:7, and 4:6. These ratios were selected based on prior studies indicating that intermediate polymer contents often provide an optimal balance between strength and ductility in plastic–sand systems [14], [17], [18]. Cement–sand control specimens were produced using a 1:2 cement-to-sand ratio with a water–cement ratio of 0.50, consistent with standard practice for masonry and paving applications. All specimens were produced as cubic samples with nominal dimensions of 50 mm × 50 mm × 50 mm. Following fabrication, specimens were conditioned under water immersion for periods of 7 and 28 days to enable direct comparison between HDPE–sand composites and cement–sand controls, consistent with common comparative testing protocols reported in the literature [17]. The mix proportions adopted for each material system and the corresponding conditioning regimes are summarized in Table I.

TABLE I
Mix Proportions And Conditioning Regime.

Mix ID	Binder type	Binder to sand ratio	Water	Conditioning
C–S	OPC cement	1:2 (cement:sand)	w/c = 0.50	7, 28 days water curing
P–S (2:8)	Recycled HDPE	2:8 (HDPE:sand)	-	
P–S (3:7)	Recycled HDPE	3:7 (HDPE:sand)	-	
P–S (4:6)	Recycled HDPE	4:6 (HDPE:sand)	-	

C. Specimen Fabrication

HDPE–sand specimens were produced using a thermal mixing and compaction process. Oven-dried sand was preheated to approximately 120–140 °C to reduce thermal gradients during mixing, after which shredded HDPE was gradually introduced and heated to a processing temperature of approximately 170–190 °C, corresponding to the melting range of HDPE. Mixing continued until a homogeneous, viscous composite was formed. The molten composite was then placed into steel molds and compacted incrementally using a hydraulic compression press at an approximate load of 5kN to reduce air voids and improve particle interlock. Specimens were allowed to cool and solidify prior to demolding. Cement–sand control specimens were prepared using conventional mixing, casting, and compaction procedures. Identical molds were used for both HDPE–sand and cement–sand specimens to ensure geometric consistency and to allow direct comparison of test results. The overall processing sequence adopted for recycled HDPE preparation and composite specimen fabrication is illustrated schematically in Fig. 2.

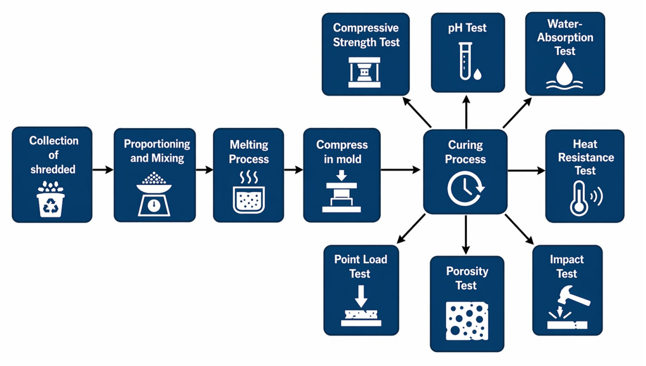

Fig. 2 Processing flow for recycled HDPE and composite fabrication.

D. *Testing Program*

The experimental testing program was designed to evaluate both mechanical performance and durability-related behavior of the composite materials, with emphasis on properties relevant to non-structural construction applications. Compressive strength was determined at 7 and 28 days using a universal testing machine, following the general procedures of ASTM C109. Water absorption was measured in accordance with ASTM D570 to assess moisture uptake and resistance to water ingress, while apparent porosity was estimated consistently across all mixes using mass–volume relationships.

Impact resistance was evaluated using a comparative drop-energy method to assess energy absorption and resistance to sudden loading, consistent with approaches reported in plastic-based composite studies [14], [16]. Exploratory thermal exposure testing was conducted by subjecting specimens to elevated temperatures of up to approximately 220 °C. Heating was applied at a controlled rate of approximately 5–10 °C/min, and specimens were maintained at the target temperature for a duration of 30 minutes. Selected samples were exposed under nominal compressive load to evaluate dimensional stability. Post-exposure behavior was assessed through visual inspection and dimensional measurements, focusing on softening, deformation, and loss of load-bearing capacity. Short-term environmental screening was carried out through pH immersion testing, in which specimens were fully submerged in water and pH was monitored at 0, 0.5, 2, 6, 12, and 24 h to assess short-term leaching behavior [15], [18]. A summary of the testing program, including test objectives and applicable standards, is provided in Table II. For each mixture and test condition, a minimum of three (n=3) replicate specimens were tested, and the reported values represent the mean results.

TABLE II
SUMMARY OF EXPERIMENTAL TESTS AND APPLICABLE STANDARDS

Test	Primary Purpose	Method / Standard
Compressive Strength	Assess load-bearing capacity	ASTM C109
Water Absorption	Measure moisture resistance	ASTM D570
Apparent Porosity	Estimate internal void content	Gravimetric method
Impact Resistance	Evaluate resistance to sudden loading	Drop-energy method (Marshall apparatus)
Thermal Exposure (Load-Bearing)	Assess high-temperature stability	Custom thermal exposure setup (≈220 °C)
pH Immersion Test	Screen environmental interaction	Laboratory immersion with pH monitoring

E. *Data Analysis*

For each test, mean values and standard deviations were calculated from replicate specimens. One-way analysis of variance (ANOVA) was used to evaluate the influence of HDPE–sand ratio on key performance indicators at a 95% confidence level. Statistical significance was assessed using p-values ($p < 0.05$), and confidence intervals were determined to quantify variability between mixture groups. Where applicable, post hoc comparisons were conducted to identify statistically significant differences between mix proportions. Comparative analysis between HDPE–sand composites and cement–sand controls was performed to identify performance trade-offs and to determine the optimal mixture proportion for non-structural construction applications.

III. RESULTS AND DISCUSSION

The mechanical, durability-related, and environmental screening performance of the HDPE–sand composites were evaluated relative to conventional cement–sand controls. The discussion focuses on identifying performance trends, optimal mix proportions, and service limitations relevant to non-structural construction applications.

A. *Compressive Strength and Failure Behavior*

The compressive strength results obtained at 7 and 28 days are presented graphically in Fig. 3. The cement–sand control specimens achieved the highest compressive strength at both curing periods, with mean values of approximately 21.6 MPa at 7 days and 20.4 MPa at 28 days. Among the HDPE–sand composites, compressive strength increased with plastic content up to the 3:7 plastic-to-sand ratio, followed by a reduction at higher plastic contents. At 28 days, the 3:7 HDPE–sand composite achieved a mean compressive strength of approximately 18 MPa, exceeding minimum strength requirements for load-bearing masonry units specified in ASTM C90 and regional standards. Statistical analysis using one-way ANOVA indicated that the variation in compressive strength across the different HDPE–sand ratios was statistically significant ($F = 4.44$, $p \approx 0.04 < 0.05$). This confirms that mixture proportion has a measurable and significant influence on the mechanical performance of the composite materials. The relatively higher mean strength observed for the 3:7 mixture is therefore not due to random variation but reflects an optimal balance between polymer binding and granular load transfer within the composite matrix. The reduction in strength observed for the 4:6 mix is attributed to diminished granular interlock and altered load-transfer mechanisms as the polymer phase becomes dominant within the composite matrix.

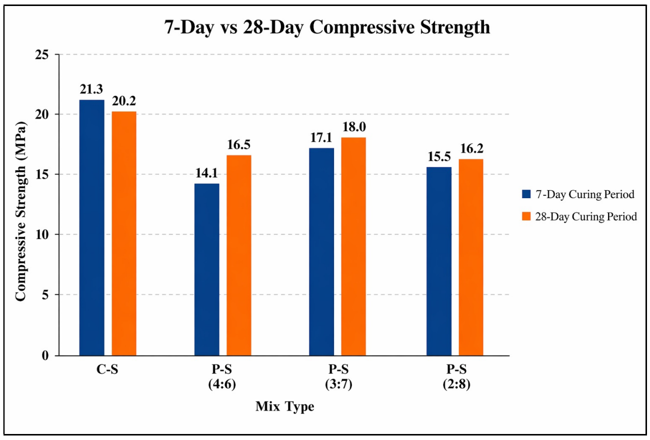

Fig. 3 Compressive strength at 7 and 28 days.

Distinct differences in failure behavior were observed between material systems, as illustrated in Fig. 4. Cement–sand specimens predominantly exhibited brittle or partially explosive failure, whereas all HDPE–sand specimens demonstrated ductile, non-explosive failure characterized by controlled cracking and post-peak integrity. This ductile behavior is advantageous for non-structural applications where energy dissipation and resistance to sudden collapse are desirable.

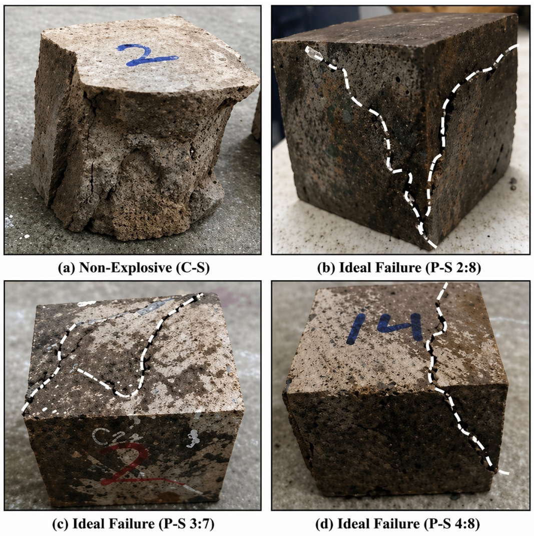

Fig. 4 Observed failure modes of specimens under compressive loading.

B. Water Absorption and Apparent Porosity

Water absorption results are shown in Fig. 5, highlighting a pronounced contrast between cement–sand and HDPE–sand composites. The cement–sand controls exhibited a mean water absorption of approximately 2.3%, whereas all HDPE–sand composites recorded absorption values below 0.5%. The lowest absorption was observed for the 3:7 mix, reflecting an optimal balance between polymer encapsulation and granular packing. This reduction in water absorption is consistent with the hydrophobic nature of HDPE and the formation of a dense composite matrix that limits interconnected pore pathways. Apparent porosity followed the same trend, with cement–sand specimens exhibiting significantly higher porosity than HDPE–sand composites. Increasing plastic content resulted in progressive reductions in porosity, although excessive plastic content did not translate into further strength gains. The low moisture uptake of the HDPE–sand composites indicates strong potential for applications in waterlogged or high-rainfall environments, particularly in tropical and coastal contexts.

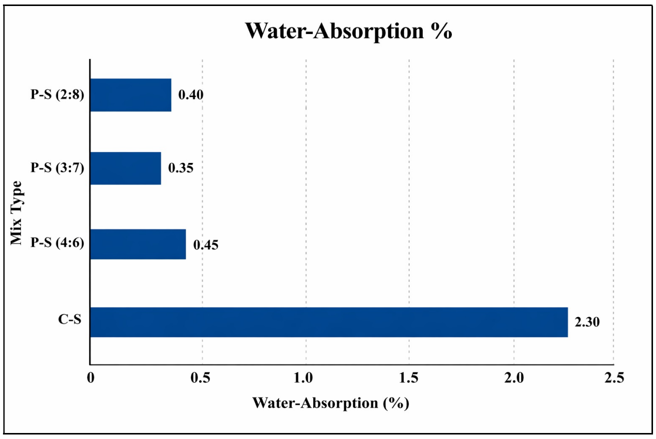

Fig. 5 Water absorption behavior.

C. Impact Resistance and Energy Absorption

Impact resistance results, presented in Fig. 6, demonstrate a substantial improvement in performance for HDPE–sand composites compared to cement–sand controls. Cement–sand specimens absorbed minimal impact energy due to their brittle nature, while HDPE–sand composites exhibited significantly higher energy absorption capacity. The 3:7 plastic-to-sand ratio consistently achieved the highest impact resistance and energy absorption values, confirming the beneficial role of the polymer binder in dissipating impact energy through viscoelastic deformation. At higher plastic contents, a reduction in energy absorption was observed, likely due to non-uniform stress distribution and reduced granular contribution. The enhanced impact resistance of HDPE–sand composites supports their suitability for paving blocks, pedestrian surfaces, and applications subjected to repeated or sudden loading.

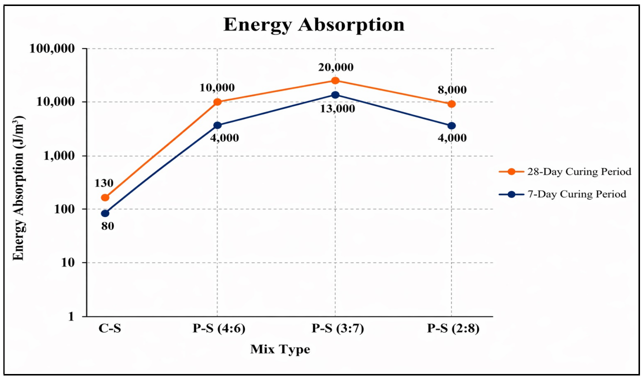

Fig. 6 Impact energy absorption.

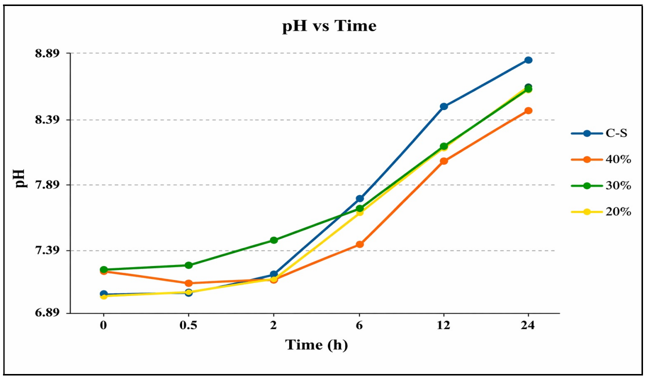

Fig. 7 Variation of pH with immersion time.

D. *Thermal Exposure Performance*

The response of the composite materials to elevated temperature exposure under nominal loading was evaluated through controlled thermal screening. Cement–sand specimens retained their geometry and load-bearing capacity after exposure to temperatures of approximately 220 °C, reflecting the non-combustible nature and high thermal mass of mineral-based materials. No visible deformation or loss of structural integrity was observed in these specimens following heating. In contrast, HDPE–sand composites exhibited noticeable softening and loss of dimensional stability when subjected to the same thermal conditions. This behavior is consistent with the thermoplastic nature of HDPE, in which increased thermal energy results in polymer chain mobility and a reduction in intermolecular bonding strength. This response is consistent with the melting temperature of HDPE (~130–137 °C) and its progressive softening at elevated temperatures, which results in reduced stiffness and loss of structural integrity under load. The observed deformation under load clearly defines a service-temperature limitation for unmodified HDPE–sand composites. These findings indicate that, in their current form, HDPE–sand composites are unsuitable for fire-exposed or high-temperature applications. However, for non-structural uses where elevated thermal exposure is not anticipated, the material remains viable. Future material modifications, such as the incorporation of fire-retardant additives or protective surface treatments, may extend the usable temperature range of HDPE-based composite construction units.

E. *Short-Term Environmental Screening (pH Response)*

The evolution of pH during short-term water immersion is presented in Fig. 7. All specimens exhibited a gradual increase in pH over the 24-hour monitoring period. Cement–sand controls produced the highest pH values due to alkaline leaching associated with cement hydration products. HDPE–sand composites exhibited lower and more stable pH levels, remaining within near-neutral to mildly alkaline ranges and within accepted freshwater environmental guidelines. The observed pH behavior suggests reduced short-term alkalinity release and potential compatibility for applications near watercourses, subject to further long-term environmental assessment.

IV. Conclusions

This study evaluated the feasibility of utilizing recycled high-density polyethylene (HDPE) as a cement-free binding phase in sand-based composite blocks for non-structural construction applications. Based on the experimental results obtained, the following conclusions are drawn:

Mechanical Performance:

HDPE–sand composites demonstrated compressive strengths comparable to conventional cement–sand blocks for non-structural applications. The 3:7 HDPE–sand ratio consistently exhibited the highest compressive strength among the polymer-based mixtures, achieving values of approximately 18 MPa at 28 days, which satisfy ASTM C90 and regional block requirements for load-bearing masonry units.

Ductility and Failure Behavior:

All HDPE–sand specimens exhibited ductile, non-explosive failure under compressive loading, in contrast to the brittle failure observed in several cement–sand control specimens. This enhanced post-peak integrity indicates improved energy dissipation and reduced risk of collapse, which is advantageous for paving and partition applications.

Durability-Related Properties:

Water absorption and apparent porosity were significantly lower for HDPE–sand composites than for cement–sand controls. Absorption values remain below 0.5% for all plastic-based mixtures, confirming strong resistance to water ingress and suitability for use in waterlogged or high-moisture environments.

Impact Resistance:

HDPE–sand composites exhibited substantially higher impact resistance and energy absorption capacity than cement–sand controls. The 3:7 mixture provided the most favorable balance between polymer content and granular load transfer, reinforcing its identification as the optimal mix proportion.

Thermal Performance Limitations:

Thermal exposure testing revealed that unmodified HDPE–sand composites lose dimensional stability at elevated temperatures approaching the softening range of HDPE. This behavior limits application in fire-exposed or high-temperature environments but clearly defines the material's current service envelope.

Environmental Screening:

Short-term pH immersion testing showed that HDPE–sand composites produced lower and more stable pH levels than cement–sand specimens, remaining within acceptable freshwater environmental ranges. This suggests reduced short-term alkalinity release and potential environmental compatibility for near-water applications.

Overall, recycled HDPE–sand composites, particularly at a 3:7 plastic-to-sand ratio, present a viable cement-free alternative for selected non-structural construction applications. Their combination of adequate compressive strength, enhanced ductility, low water absorption, and high impact resistance supports their use in paving blocks, pedestrian infrastructure, and partition elements. Future research should focus on thermal modification strategies, long-term environmental performance, and scale-up testing to facilitate broader adoption in sustainable construction practice.

ACKNOWLEDGMENT

The authors gratefully acknowledge the technical support provided by the staff of the Highway and Transportation Laboratory and the Structures Laboratory, Department of Civil and Environmental Engineering, The University of the West Indies, St. Augustine Campus. Appreciation is also extended to Flying Tree Environmental Management Ltd. for supplying recycled HDPE materials and facilitating access to processing equipment. The assistance of laboratory technicians and support staff during specimen preparation and testing is sincerely acknowledged.

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