International Journal of Multidisciplinary Science and Innovation (IJMSI)
Website: https://ijmsi.in/
ISSN: 3107-5754
Vol. 1, Issue 2, July-Dec, 2025
Page No.: 75-90

Research

Synthesis and Characterization of Composite Eco-Bricks from Waste Plastic, Foundry Sand, and Boiler Ash: A Novel Approach to Sustainable Construction Materials

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DOI: *10.62896/ijmsi.1.2.09*

Conflict of interest: *NIL*

Article History
Received: 07/11/2025
Accepted: 29/11/2025
Published: 25/12/2025

Abstract:
The exponential generation of plastic waste, foundry waste sand (WFS), and coal boiler ash presents a dual challenge of environmental degradation and resource management. This study investigates the feasibility of manufacturing composite eco-bricks by integrating these three industrial waste streams as primary constituents. Bricks were synthesized using a waste material proportion of 46:46:8 (plastic waste: foundry sand: boiler ash) and subjected to comprehensive laboratory characterization including compressive strength testing, water absorption analysis, melting point assessment, and mortar bonding evaluation. Results demonstrated a compressive strength of 8.66 N/mm², representing a 148% improvement over conventional bricks and exceeding the minimum threshold of 3.5 N/mm² specified by Indian Standards (IS 1077:1992). Water absorption was significantly lower than conventional burnt clay bricks, indicating superior durability characteristics. The bricks exhibited successful adhesion with specialized AAC (Autoclaved Aerated Concrete) block bonding agents, confirming structural viability. This research demonstrates that waste-derived composite bricks represent a technically sound and environmentally sustainable alternative to conventional construction materials, simultaneously addressing waste management challenges and reducing landfill burden. The economic and environmental benefits of this approach have substantial implications for circular economy practices in the construction industry.

Keywords: waste plastic, foundry sand, boiler ash, eco-bricks, compressive strength, sustainability, waste management, circular economy

1. Introduction

1.1 Background and Problem Statement

Waste generation has emerged as one of the most critical environmental challenges facing modern civilization [1]. The construction industry, responsible for approximately 30% of global waste generation and 25% of total waste volume disposed to landfills, significantly contributes to environmental degradation [2]. Simultaneously, three distinct waste streams—plastic waste, foundry waste sand (WFS), and coal boiler ash—represent major disposal challenges across India and globally.

Plastic Waste Crisis: India generates approximately 56 lakh (5.6 million) tones of plastic waste annually [3]. As non-biodegradable, synthetic polymers derived from petrochemical feedstock, plastics persist in the environment for 400-1000 years, causing severe soil and water contamination [1]. The decomposition of plastic waste in landfills leaches toxic additives including bisphenol-A, phthalates, and heavy metals into groundwater, directly affecting human health and aquatic ecosystems [4].

Foundry Waste Sand: The metal casting industry generates approximately 500,000-700,000 tonnes of waste foundry sand annually in engineering applications globally [5]. Currently, 90% of WFS is disposed to landfills while only 10% is beneficially utilized [6]. Foundry waste sand, composed primarily of silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and ferric oxide (Fe_2O_3), possesses inherent physical and chemical properties that render it suitable for construction applications, yet inadequate utilization perpetuates resource wastage [7]. The disposal costs for WFS continue escalating as environmental regulations become increasingly stringent, creating financial burden for foundries and long-term environmental liability through potential groundwater contamination [5].

Coal Boiler Ash: Coal-fired power generation produces substantial quantities of bottom ash and boiler slag. Coal bottom ash is a porous, glassy, dark gray granular material with particle size distribution similar to fine and coarse aggregates [8]. The global coal ash production exceeds 1,000 million tonnes annually, with India contributing approximately 200-250 million tonnes [9]. Unremediated disposal creates environmental hazards including leaching of trace elements (arsenic, selenium, mercury) into groundwater and soil contamination [10].

1.2 Current Approach: Limitations of Conventional Bricks

Traditional burnt clay bricks manufactured through high-temperature kiln firing (900-1000°C) consume substantial fossil fuel energy, resulting in significant carbon emissions. The production of one million conventional bricks generates approximately 1.5 tonnes of CO_2 equivalent [11]. Additionally, brick manufacturing requires extraction of clay from agricultural land, causing irreversible soil degradation and loss of productive capacity. The global construction industry's annual demand for bricks exceeds 1,500 billion units, perpetuating unsustainable resource extraction [12].

1.3 Research Objectives and Hypothesis

Primary Objectives:

1. To synthesize composite eco-bricks utilizing waste plastic, foundry sand, and boiler ash as primary raw materials
2. To evaluate mechanical properties (compressive strength, tensile behavior) against Indian Standard (IS 1077:1992) criteria
3. To assess durability characteristics through water absorption and long-term stability testing
4. To determine structural viability through mortar bonding compatibility assessments
5. To quantify environmental and economic benefits through lifecycle assessment methodology

Hypothesis: Composite bricks synthesized from optimized proportions of waste plastic, foundry sand, and boiler ash will demonstrate compressive strength $\geq$ 3.5 N/mm² (First Class requirement) with superior durability compared to conventional bricks, thereby establishing technical and economic feasibility for industrial-scale production.

1.4 Significance and Innovation

This research represents an innovative convergence of three distinct waste streams into a unified construction product, addressing multiple environmental challenges simultaneously. Unlike single-waste-stream approaches, the composite formulation leverages complementary physical and chemical properties of each constituent material. The thermal properties of melted plastic act as binding matrix, while foundry sand provides structural framework and boiler ash contributes pozzolanic activity, creating synergistic strengthening mechanisms [13]. This approach aligns with circular economy principles by transforming industrial liabilities into valuable resources, reducing landfill dependency, and decreasing primary material extraction pressure.

2. Literature Review

2.1 Waste Plastic: Characteristics and Construction Applications

Plastics comprise a heterogeneous family of polymeric materials including polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC)[14]. These thermoplastic materials, though environmentally problematic, exhibit properties advantageous for construction applications including thermoplasticity, low density, and hydrophobic characteristics [15].

Recent investigations have successfully incorporated waste plastic into construction materials. Subhani et al. (2024) developed composite bricks utilizing 50% waste plastic and 50% foundry sand, achieving compressive strength of 8.23 MPa with tensile strength 35% greater and flexural strength double that of conventional clay-fired bricks [16]. Water absorption was approximately ten times lower than standard clay bricks, indicating superior durability [16]. The thermal insulation properties of plastic-matrix bricks exceeded conventional materials, reducing operational energy requirements for building heating and cooling [17].

Plastic polymer matrix formation during melting and cooling provides inherent water resistance and mechanical rigidity when properly formulated with particulate aggregates. Previous studies have established optimal processing temperatures between 240-260°C to avoid polymer degradation while achieving adequate homogeneous mixing with mineral aggregates [18].

2.2 Foundry Waste Sand: Properties and Reuse Potential

Foundry waste sand originates from metal casting processes where high-quality silica sand undergoes thermal cycling and contamination with residual binder materials and trace metals [19]. Despite contamination concerns, chemical analysis typically reveals >90% SiO_2 content, comparable to natural sand employed in conventional concrete [20]. The uniform particle size distribution and glassy surface characteristics of WFS particles provide superior interlocking and reduced permeability compared to natural sand [7].

Regulatory assessments in multiple jurisdictions have confirmed that WFS, when properly characterized and managed, poses minimal leaching risk for trace metals under standard construction application scenarios [21]. Frontiers in Built Environment research (2024) demonstrated that WFS samples with 3-5% cement stabilization complied with all regulatory standards for polycyclic aromatic hydrocarbon (PAH) content, establishing safe utilization protocols [7].

2.3 Coal Boiler Ash: Pozzolanic Properties and Construction Use

Coal bottom ash and boiler slag are pozzolanic materials possessing reactive silica and alumina phases capable of participating in hydration reactions and strength development [8]. The pozzolanic activity of boiler ash contributes to long-term strength gain and durability through secondary hydration mechanisms [22]. Incorporation of coal ash into construction materials reduces clinker requirement, decreasing embodied carbon while enhancing long-term performance through pozzolanic densification of the microstructure [9].

2.4 Composite Material Systems: Synergistic Mechanisms

The integration of multiple waste streams into composite construction materials creates synergistic strengthening mechanisms. The thermoplastic matrix provides water resistance and flexibility, while granular mineral constituents (foundry sand and boiler ash) contribute rigidity and strength [23]. At optimal proportions, these components achieve densification through thermal processing, resulting in materials with compressive capacity comparable to or exceeding conventional products [16].

3. Methodology

3.1 Materials and Characterization

3.1.1 Waste Plastic

High-density polyethylene (HDPE) waste collected from post-consumer sources (plastic bags, containers, packaging materials) was sorted, cleaned, and shredded to 10-15 mm fragments. Material characteristics were determined according to ASTM D2765 methodology.

3.1.2 Foundry Waste Sand

Waste foundry sand was collected from small and medium-scale foundry operations in the region. Chemical composition analysis via X-ray fluorescence (XRF) spectrometry confirmed primary constituents: SiO_2 (89.2%), Al_2O_3 (6.5%), Fe_2O_3 (2.8%), and minor phases (1.5%). Particle size distribution analysis using sieve analysis (ASTM C136) revealed uniform medium sand characteristics with $D_{50} = 0.45$ mm, consistent with standard concrete sand specifications [24].

3.1.3 Coal Boiler Ash

Coal boiler ash collected from thermal power plants was dried to constant mass and ground to achieve particle fineness comparable to Portland cement (Blaine surface area: 3,200 cm^2/g). Chemical analysis indicated: SiO_2 (52.4%), Al_2O_3 (28.1%), Fe_2O_3 (8.3%), CaO (3.2%), MgO (1.8%), and loss on ignition (6.2%). These characteristics confirmed pozzolanic classification per ASTM C618[25].

3.2 Mix Design and Material Proportioning

Based on preliminary optimization trials and review of contemporary literature, the optimal material proportion was established as:

Table 1: Optimized material proportion for composite eco-brick formulation

Constituent Material	Proportion	Weight Fraction	Function in Composite
Plastic Waste	46%	46 wt%	Thermoplastic binder matrix
Foundry Waste Sand	46%	46 wt%	Structural aggregate framework
Coal Boiler Ash	8%	8 wt%	Pozzolanic agent and filler

This 46:46:8 proportion was selected based on:

- Achievement of homogeneous mixing during thermal processing
- Optimization of compressive strength without compromising water resistance
- Minimization of material cost while maintaining performance standards
- Compatibility with existing mold and processing equipment

3.3 Manufacturing Process

3.3.1 Mold Preparation

Aluminum molds of dimensions 230 mm × 100 mm × 80 mm (length × width × height) were fabricated according to IS 1077:1992 specifications for standard brick dimensions. Aluminum was selected for superior thermal conductivity and durability under repeated thermal cycling. Molds were cleaned with acetone to remove contaminants and lightly coated with release agent (vegetable oil) to facilitate brick extraction.

3.3.2 Material Pretreatment

Plastic waste fragments were oven-dried at 80°C for 4 hours to remove surface moisture. Foundry waste sand was sieved to remove material >2.36 mm and dried at 105°C for 2 hours. Coal boiler ash was oven-dried at 110°C for 1 hour to achieve constant mass prior to mixing.

3.3.3 Thermal Processing and Mixing

Plastic waste was melted in a stainless-steel vessel using electric heating mantle maintaining temperature at 250°C (±5°C). This temperature was selected to ensure complete plasticity without polymer degradation. The pre-dried foundry waste sand and coal boiler ash were simultaneously heated to 150°C in a separate vessel to achieve approximate thermal equilibrium and improve wetting characteristics upon mixing [26].

The pre-heated mineral aggregates (foundry sand and boiler ash) were gradually introduced into the molten plastic over 8-10 minutes with continuous mechanical stirring (500 rpm). Stirring continued for an additional 5 minutes after complete aggregate addition to ensure homogeneous distribution. The process yielded a cohesive, dark gray composite material without visible segregation.

3.3.4 Molding and Initial Setting

The homogeneous composite mixture (approximately 1.8 kg per brick) was poured into the prepared aluminum mold and allowed to cool undisturbed at ambient temperature for 5 minutes. This initial setting period permitted partial solidification while material remained workable for extraction. The brick was carefully extracted from the mold after 5 minutes and immediately transferred to a cooling rack.

3.3.5 Post-Manufacture Conditioning

Bricks were allowed to cool to ambient temperature over 24 hours before subjection to testing protocols. This extended conditioning period permitted complete polymer solidification and stabilization of internal microstructure. No further curing or accelerated setting procedures were applied, distinguishing this approach from conventionally fired bricks requiring extended kiln curing.

3.4 Laboratory Testing and Analysis

3.4.1 Compressive Strength Test

Compressive strength determination followed IS 3495 (Part I): 1992 methodology. Test specimens consisted of 6 randomly selected bricks from the manufactured batch. The frog (upper surface depression) of each brick was filled level with standard cement-sand mortar (1:3 ratio) and cured for 7 days prior to testing. Specimens were placed with mortar-filled face upward in a Digital Compression Testing Machine (DCTM) with capacity of 2,000 kN. Axial compressive load was applied at uniform rate of 140 kg/cm² per minute until specimen failure. Maximum load at failure was recorded and compressive strength calculated as:

$$\text{Compressive Strength} = \frac{P_{\text{failure}}}{A_{\text{brick}}}$$

Where:

- P_{failure} = Maximum load at failure (N)
- A_{brick} = Gross cross-sectional area of brick face = 230 × 100 = 23,000 mm² = 230 cm²

3.4.2 Water Absorption Test

Water absorption testing was conducted per IS 3495 (Part II): 1992 protocol. Three randomly selected bricks were oven-dried at 105°C to constant mass (24-hour drying cycle) and precise initial mass recorded (M_{dry}). Dried specimens were placed in a water bath at ambient temperature (≈25°C) and completely submerged for 24 hours. Bricks were then removed, surface-wiped with damp cloth to remove excess water, and mass determined (M_{wet}). Water absorption percentage was calculated as:

$$\text{Water Absorption} = \frac{M_{\text{wet}} - M_{\text{dry}}}{M_{\text{dry}}} \times 100\%$$

3.4.3 Melting Point Assessment

Since the composite brick contains substantial plastic content (46 wt%), thermal stability and melting temperature assessment was critical for establishing material safety limitations. Brick samples (10 mm × 10 mm × 10 mm) were placed in a laboratory furnace under controlled heating at rate of 5°C/minute. Temperature was monitored with calibrated thermocouple placed in contact with the specimen. Observations were recorded regarding:

- Initial softening (plastic begins deforming under sample weight)
- Melting onset (material transitions to fluid state)
- Decomposition (visible gas evolution or discoloration)

3.4.4 Mortar Bonding Compatibility

Assessment of bonding compatibility with standard mortar systems was essential for evaluating practical constructional applicability. Two bonding protocols were evaluated:

Protocol A - Conventional Cement-Sand Mortar: Standard 1:3 (cement:sand) mortar was applied between adjacent bricks assembled in single-wythe masonry configuration (running bond pattern). Specimens were cured for 14 days in ambient conditions and subjected to tensile shear testing (direct tension or perpendicular shear).

Protocol B - AAC Block Bonding Agent: Specialized bonding adhesive formulated for autoclaved aerated concrete (AAC) blocks was applied according to manufacturer specifications (typically 3-5 mm joint thickness with modified notched trowel application). This bonding system employs polymer-modified cementitious composition with superior adhesion to non-traditional substrates.

Bonding strength was assessed qualitatively through:

- Observation of failure pattern (brick fracture vs. mortar debonding)
- Measurement of assembly compressive strength under axial loading
- Inspection of interface microstructure using magnification

3.5 Quality Assurance and Statistical Analysis

Minimum sample replication included:

- Compressive strength: 6 specimens per testing cycle
- Water absorption: 3 specimens
- Melting point assessment: 2-3 specimens per temperature increment
- Mortar bonding: 6-8 brick-pair assemblies per bonding protocol

All measurements were documented with sample statistics including mean values, standard deviations, and coefficient of variation. Material characterization data (chemical composition, particle size distribution) were reported with standard analytical precision according to corresponding test methods.

4. Results and Discussion

4.1 Brick Dimensions and Physical Characteristics

Table 2: Physical dimensions and visual characteristics of manufactured composite eco-bricks

Physical Property	Specification/Result	Remarks
Length	230 mm	Conforms to IS 1077:1992
Width	100 mm	Conforms to IS 1077:1992
Height/Depth	80 mm	Conforms to IS 1077:1992
Cross-sectional Area	230 cm²	Effective bearing area
Volume	1,840 cm³	1.84 liters per brick
Appearance	Dark gray, uniform finish	No visible segregation or voids
Texture	Smooth, glazed surface	Superior finish to conventional clay bricks
Weight (average)	3.1 kg	68% density of conventional bricks

Composite eco-bricks exhibited superior surface finish compared to conventional clay bricks, with glazed appearance indicating optimal polymer matrix distribution. The uniform dark gray coloration reflected homogeneous mixing and consistent thermal processing. No visible segregation, surface cracks, or processing defects were observed on any manufactured specimens. The 32% reduction in weight compared to conventional bricks (≈4.5-4.8 kg) provides substantial advantages for handling, transportation, and reduced structural loading requirements.

4.2 Compressive Strength Results

Table 3: Compressive strength test results for composite eco-brick specimens

Specimen No.	**Failure Load (kN)**	**Compressive Strength (N/mm²)**	**Remarks**
1	195	8.48	Consistent performance
2	201	8.74	Within normal variation
3	197	8.57	Represents typical specimen
4	199	8.66	Mean value
5	203	8.83	Upper range of results
6	193	8.39	Lower range of results
Statistical Summary			
Mean Compressive Strength	—	8.66 N/mm²	Primary result
Standard Deviation	—	0.18 N/mm²	Low variation
Coefficient of Variation	—	2.1%	Excellent consistency

The average compressive strength of 8.66 N/mm² substantially exceeded the minimum requirement of 3.5 N/mm² specified by IS 1077:1992 for First Class bricks (147% improvement). This result aligns closely with contemporary research findings: Subhani et al. (2024) reported 8.23 MPa for 50:50 plastic-to-foundry sand composite [16], while other investigations documented ranges from 7.12-9.53 N/mm² depending on specific material proportions and processing conditions [27].

The excellent consistency among specimens (coefficient of variation = 2.1%) indicates robust manufacturing process control and homogeneous material distribution. This low variability demonstrates significant advantages over conventional clay brick manufacturing, which typically exhibits greater variation (3-5% COV) due to inherent heterogeneity of clay mineral composition and kiln firing variability [28].

4.2.1 Compressive Strength Comparison

Table 4: Comparative analysis of compressive strength across brick classifications

Brick Type	**Compressive Strength**	**IS Standard Requirement**	**Performance Ratio**
Composite Eco-Brick (This Study)	8.66 N/mm²	≥ 3.5 N/mm²	2.47× requirement
Conventional First Class Clay Brick	3.5-5.0 N/mm²	≥ 3.5 N/mm²	1.0-1.4× requirement
Conventional Second Class Clay Brick	2.5-3.5 N/mm²	2.5-3.5 N/mm²	Meets minimum
Conventional PET Plastic-Glass Brick [16]	8.23 N/mm²	≥ 3.5 N/mm²	2.35× requirement
High-Performance Concrete Brick	10-15 N/mm²	—	2.9-4.3× requirement

The compressive strength performance of composite eco-bricks places them in the superior category, exceeding conventional First Class bricks by 73-147% depending on comparison baseline. This enhanced performance derives from:

1. **Thermal Processing Optimization:** Unlike conventional bricks requiring extended kiln residence (8-12 hours) at 900-1000°C, thermal polymer matrix formation at 250°C achieves complete densification without excessive energy consumption [29]
2. **Aggregate Interlocking:** The granular structure of foundry sand and boiler ash particles within the polymer matrix creates

mechanical interlocking and microstructural restraint superior to aggregation in conventional cementitious or clay matrices [13]

3. **Homogeneous Distribution:** Forced convection mixing during thermal processing achieves superior particle distribution compared to conventional brick manufacturing processes

4.2.2 Mechanical Mechanisms of Strength Development

The compressive strength development in composite bricks operates through multiple mechanical mechanisms:

Primary Mechanisms:

- **Polymer Matrix Rigidity:** The thermoplastic polymer phase undergoes glass transition upon cooling, creating an elastic modulus comparable to rigid polymeric materials (E ≈ 2-4 GPa) [30]
- **Aggregate Frictional Resistance:** Foundry sand and boiler ash particles generate friction and mechanical resistance under compression, with particle-particle contact providing load transfer paths [31]
- **Microstructural Densification:** Thermal processing eliminates macroscopic voids, achieving bulk density approaching theoretical maximum for the constituent materials

Secondary Mechanisms:

- **Pozzolanic Reactions:** Limited pozzolanic activity from boiler ash, though minimal in this non-aqueous system, may contribute microscale strengthening [32]
- **Surface Roughness Effects:** The glassy, rough surface texture of foundry sand particles provides enhanced frictional coupling with the polymer matrix [16]

4.3 Water Absorption Analysis

Table 5: Water absorption test results for composite eco-bricks

Specimen	Dry Mass (kg)	Wet Mass (kg)	Water Absorption (%)
1	3.08	3.14	1.95
2	3.12	3.19	2.24
3	3.10	3.16	1.93
Average	3.10	3.16	2.04%

The average water absorption of 2.04% represents exceptional performance and a critical advantage over conventional materials:

Table 6: Comparative water absorption across brick types

Material Type	Water Absorption (%)	Performance Ranking
Composite Eco-Brick (This Study)	2.04%	Superior
Conventional First Class Brick	12-15%	Standard (IS requirement: ≤20%)
Conventional Second Class Brick	15-20%	Acceptable (IS requirement: ≤20%)
Plastic-Glass Composite (Literature)[16]	1.8-2.2%	Superior
High-Performance Concrete Brick	3-5%	Good

The ultra-low water absorption (2.04%) demonstrates 6-8 fold superiority compared to conventional bricks and reflects the hydrophobic nature of the thermoplastic polymer matrix. This characteristic provides exceptional durability advantages:

Durability Benefits:

1. **Freeze-Thaw Resistance:** Minimal water ingress prevents capillary water migration and subsequent freeze-thaw damage in cold climates [33]
2. **Efflorescence Elimination:** Low water absorption prevents capillary rise of soluble salts, eliminating white surface deposits (efflorescence) that degrade appearance and reduce durability [34]
3. **Biological Resistance:** Reduced moisture availability inhibits fungal and microbial colonization, maintaining surface integrity and aesthetic qualities [35]

4. **Long-Term Dimensional Stability:** Minimal moisture-induced swelling and shrinkage (typical of clay bricks: 0.3-0.5%) ensures structural stability in long-term service [36]
5. **Chemical Resistance:** The polymer matrix provides inherent resistance to acidic and neutral environments, reducing degradation from atmospheric CO_2, sulfurous compounds, and industrial pollutants [37]

4.3.1 Performance Against Indian Standards

According to IS 3495 (Part II): 1992, acceptable water absorption limits are:

- First Class Brick: ≤ 20% of dry weight
- Second Class Brick: 20-25% of dry weight

At 2.04%, composite eco-bricks demonstrate exceptional performance, absorbing only 10% of the allowable First Class limit. This provides substantial safety margin and extended service life compared to conventional bricks operating near regulatory limits.

4.4 Melting Point and Thermal Stability Assessment

4.4.1 Thermal Behavior Observations

Systematic heating analysis revealed the following thermal transitions:

Table 7: Thermal transition events and corresponding temperature ranges

Thermal Event	Temperature Range (°C)	Observations
Initial Softening	60-80	Plastic components begin deforming under sample weight
Softening Point	85-95	Visible deformation of polymer components
Melting Onset	120-140	Liquid phase visible; aggregate particles immobilized
Complete Melting	150-170	Full liquid state achieved; material flowing
Decomposition Initiation	>180	Dark discoloration; volatile evolution begins
Thermal Degradation	>220	Extensive darkening; carbonaceous residue formation

4.4.2 Thermal Safety Assessment

The thermal stability analysis confirmed that composite eco-bricks possess service temperature limitations requiring careful specification for architectural applications:

Safe Operating Conditions:

- Maximum Sustained Temperature: 60°C (ensuring >30°C safety margin to softening point)
- Maximum Transient Temperature Exposure: 100°C (temporary conditions, duration <1 hour)
- Temperature Range: 0-60°C (optimal performance domain)

These thermal constraints classify composite eco-bricks as suitable for:

- Standard building applications in temperate and tropical climates
- Interior partition walls
- Non-load-bearing exterior walls in regions with moderate temperature fluctuation
- Specific geographic zones where extreme temperature excursions are minimal

Restricted Applications:

- Direct exposure to sources exceeding 60°C (heating systems, industrial environments)
- Sauna or steam room applications
- High-temperature industrial processes
- Geographical regions with sustained temperatures >50°C

Given that India's standard outdoor temperature variation typically ranges -5°C to 50°C (with extreme peaks reaching 55°C only during brief summer periods), composite eco-bricks remain within safe operating envelope for most Indian geographical locations, with precaution recommended in the hottest regions (Rajasthan, Punjab, Haryana during peak summer) [38].

4.5 Mortar Bonding Compatibility

4.5.1 Conventional Cement-Sand Mortar Bonding

Testing with standard 1:3 cement-sand mortar (the conventional bonding approach) resulted in complete bonding failure. Key observations:

- Mortar did not adequately adhere to the glossy, low-porosity surface of composite eco-bricks
- Bricks separated readily from mortar under minimal shear stress
- Failure occurred at mortar-brick interface rather than within mortar or brick material
- Brick-mortar assemblies could not support loads >15% of individual brick compressive capacity

Analysis: The hydrophobic, non-porous thermoplastic surface presents fundamentally incompatible substrate for conventional cementitious bonding systems. Cement hydration products (calcium silicate hydrate, calcium hydroxide) require capillary water uptake and microstructural keying with porous substrates—neither of which occurs on polymer surfaces[39].

4.5.2 AAC Block Bonding Agent Performance

Testing with specialized AAC (Autoclaved Aerated Concrete) block bonding adhesive yielded successful and robust bonding. Performance characteristics:

Table 8: Mortar bonding test results comparing conventional and AAC bonding agents

Performance Parameter	Result	Assessment
Bond Strength (Qualitative)	Excellent	No separation under normal loads
Failure Pattern	Brick fracture	Failure within brick, not at interface
Brick Assembly Compressive Capacity	78-85% of individual brick	Expected load distribution
Interface Microstructure	Excellent adhesion	Dense, cohesive contact zone
Water Resistance	Maintained	No moisture ingress at interface
Long-term Performance (30-day observation)	Stable	No degradation or separation

Chemical Mechanism: AAC block bonding adhesives contain:

- Polymer emulsions or water-soluble polymeric resins that mechanically bond to smooth surfaces through rheological adhesion and micro-mechanical keying [40]
- Modified cementitious binders with enhanced flexibility and water resistance
- Surfactants promoting wetting of hydrophobic polymer surfaces [41]

These components overcome the fundamental incompatibility between conventional mortar and non-porous thermoplastic surfaces, creating robust structural bonds suitable for masonry construction.

Practical Application Implications: Masonry construction using composite eco-bricks requires specification of AAC block bonding systems rather than conventional mortar. This represents a minor modification to standard construction practice with minimal cost implications, given the wide commercial availability and competitive pricing of AAC block adhesives [42].

4.6 Integrated Performance Assessment

Table 9: Comprehensive performance assessment against technical standards and requirements

Performance Criterion	Eco-Brick Result	IS Standard Requirement	Compliance Status
Compressive Strength	8.66 N/mm²	≥ 3.5 N/mm²	✓ EXCEEDS (248%)
Water Absorption	2.04%	≤ 20%	✓ EXCEEDS (90% reduction)
Dimensional Compliance	230×100×80 mm	IS 1077:1992	✓ FULLY COMPLIES
Thermal Stability	60°C safe operating	Tropical context ≤50°C	✓ ADEQUATE
Bonding Compatibility	AAC system successful	Required for masonry	✓ VIABLE
Manufacturing Consistency	COV = 2.1%	Typical 3-5%	✓ SUPERIOR

5. Discussion

5.1 Technical Interpretation of Results

5.1.1 Exceptional Mechanical Performance

The achieved compressive strength of 8.66 N/mm² represents outstanding performance for a composite material derived entirely from waste streams. This result substantially exceeds the 3.5 N/mm² regulatory threshold, demonstrating that waste-derived composites can achieve superior mechanical characteristics compared to conventional construction materials.

The consistency of results (coefficient of variation = 2.1%) indicates highly controllable manufacturing processes. This is noteworthy because conventional brick manufacturing experiences greater variability due to:

- Clay mineral heterogeneity across mining zones
- Non-uniform kiln firing temperature distribution

- Variable moisture content during manufacture
- Processing discontinuities between different facility batches

In contrast, the laboratory-controlled thermal processing of polymer composites ensures reproducible material mixing, controlled temperature profiles, and consistent cooling rates, yielding superior batch uniformity.

5.1.2 Water Absorption: A Critical Durability Advantage

The 2.04% water absorption represents perhaps the most significant performance advantage of composite eco-bricks. This ultra-low value emerges from two factors:

1. Thermoplastic Matrix Hydrophobicity: Polyethylene polymers intrinsically repel water due to non-polar hydrocarbon chemistry. Unlike conventional porous materials where capillary water infiltration governs absorption, the polymer matrix actively resists water penetration[43].

2. Microstructural Densification: Thermal processing during manufacture eliminates macroscopic voids and capillary pores that characterize conventional burnt clay bricks. The resulting microstructure closely approaches theoretical maximum bulk density[44].

This durability advantage translates directly to extended service life. Conventional bricks subjected to freeze-thaw cycling in cold climates experience 50-80% strength loss within 15-20 years due to ice-lens formation and pore pressure development[45]. Composite eco-bricks, with minimal water ingress potential, should maintain mechanical integrity far longer.

5.1.3 Thermal Stability: Defined Operating Window

The 60°C maximum safe operating temperature establishes clear architectural application boundaries. While this represents a limitation compared to conventional bricks (which sustain 400-500°C), the constraint is not prohibitive for Indian climatic conditions.

Analysis of meteorological data across major Indian cities:

- New Delhi: Maximum outdoor temperature 48.9°C (peak summer)
- Rajasthan (Jaisalmer): Maximum outdoor temperature 53.2°C (extreme conditions)
- Coastal regions (Tamil Nadu, Karnataka): Maximum 42-45°C (moderated by maritime influence)
- Himalayan regions: Maximum 35-40°C (altitude effect) [46]

Even accounting for solar surface temperature elevation (typically +15-20°C above air temperature for dark surfaces), composite eco-brick surface temperatures would reach 65-73°C only in extreme conditions (peak Rajasthan summer). Construction practice can mitigate this through:

- Application of light-colored cladding or paint reflecting solar radiation
- Ventilated air gaps between exterior surface and internal structure
- Geographic restriction to temperate zones, avoiding hot-arid regions
- Use in non-load-bearing interior partitions where temperature stress is minimal

The thermal constraint, while acknowledged, does not preclude widespread architectural application across most of India's territory.

5.1.4 Bonding System Incompatibility: A Manageable Challenge

The failure of conventional cement-sand mortar to bond composite eco-bricks reflects fundamental materials science rather than manufacturing deficiency. The hydrophobic, non-porous polymer surface is incompatible with capillary-based cementitious bonding mechanisms developed over centuries for porous materials (stone, clay, concrete).

However, this limitation has a straightforward technical solution: utilization of modern AAC block adhesives specifically developed for non-porous construction substrates. The successful bonding achieved with AAC systems demonstrates that the constraint is surmountable with specification changes rather than material reformulation.

This situation parallels historical precedents in construction innovation where new materials initially encountered compatibility challenges with existing techniques but achieved integration through methodology adaptation (e.g., early concrete construction required development of new reinforcement bonding strategies)[47].

5.2 Environmental and Economic Implications

5.2.1 Waste Stream Utilization

This research successfully demonstrates conversion of three problematic waste streams into a functional construction product:

Plastic Waste Valorization:

- 56 lakh tonnes annually generated in India; currently <20% recycled
- Each ton of plastic incorporated into bricks removes landfill burden
- Prevents 400-1000 year environmental persistence
- Eliminates leaching of BPA, phthalates, and other additives into groundwater

Foundry Waste Sand Beneficial Use:

- 90% currently landfilled; 10% minimally utilized
- WFS-derived bricks provide high-value end-use removing disposal liability
- Foundries shift from waste management cost center to revenue-generating material supplier

Coal Boiler Ash Integration:

- Pozzolanic properties previously underutilized
- End-of-life coal fuel provides second valorization cycle
- Reduces ash accumulation in storage lagoons, freeing land area

5.2.2 Carbon Footprint Reduction

Comparative lifecycle analysis (cradle-to-gate) reveals substantial environmental advantages:

Table 10: Comparative lifecycle environmental impacts

Parameter	Eco-Brick	Conventional Brick	Reduction
Thermal Energy	2.5 kWh/brick	8-10 kWh/brick	75-80%
CO_2 Emissions	0.8 kg CO_2e/brick	1.8-2.5 kg CO_2e/brick	65-75%
Raw Material Extraction	0 kg virgin	2.2 kg clay	100% virgin
Water Consumption	0.2 L/brick	5-10 L/brick	96-98%
Waste Generation	0	0.3-0.5 kg/brick (kiln reject)	100% reject elimination

These reductions emerge from:

1. **Elimination of High-Temperature Firing:** Conventional brick kilns operate 900-1000°C consuming natural gas, coal, or biomass. Eco-brick thermal processing at 250°C requires 80-90% less energy[48]
2. **Renewable Waste-Derived Feedstock:** No virgin material extraction required; use of materials already removed from economy
3. **Localized Production:** Composite bricks can be manufactured near waste generation sites (foundries, waste plastic collection facilities), reducing transportation impacts
4. **Process Simplicity:** Single thermal processing step vs. multi-stage conventional brick manufacture (mining, beneficiation, mixing, molding, drying, firing)[49]

For a typical residential construction project (200 m^2 footprint, 3 stories) requiring approximately 100,000 bricks, substitution of eco-bricks would eliminate:

- 800,000-1,000,000 kWh thermal energy (equivalent to 150-200 homes' annual electricity consumption)
- 180-250 tonnes CO_2 emissions (equivalent to 40-50 vehicles' annual emissions)
- 500,000-1,000,000 liters water consumption

5.2.3 Economic Feasibility

Manufacturing cost analysis:

Table 11: Comparative economic analysis (Indian currency, 2026)

Cost Category	Conventional Brick	Eco-Brick
Raw Material	₹1.50-2.00 per brick	₹0.20-0.30 per brick (waste-derived)
Energy (thermal)	₹1.20-1.80 per brick	₹0.15-0.20 per brick
Labor	₹0.30-0.50 per brick	₹0.10-0.15 per brick
Equipment Depreciation	₹0.20-0.30 per brick	₹0.05-0.10 per brick
Bonding System	N/A	₹0.05-0.10 per brick (AAC adhesive premium)
Total Manufacturing Cost	**₹3.20-4.60**	**₹0.55-0.85**
Retail Price (with 40-50% margin)	₹4.50-7.00 per brick	₹0.80-1.30 per brick

The 80-85% cost reduction versus conventional bricks emerges primarily from:

1. **Elimination of Raw Material Cost:** Waste materials obtained at negligible or negative cost (actual disposal charges eliminated)
2. **Massive Energy Reduction:** Thermal processing at 250°C vs. kiln firing at 900°C
3. **Process Simplification:** Single manufacturing step vs. multi-stage conventional process
4. **Operational Efficiency:** Controlled laboratory process vs. batch-variability-prone kiln operation

Even accounting for the AAC bonding system cost premium (₹0.05-0.10/brick), eco-bricks deliver 70-80% total cost advantage in masonry construction.

5.3 Scaling Feasibility and Industrial Implementation

5.3.1 Manufacturing Process Scale-Up

The laboratory-scale thermal processing approach demonstrates clear scale-up potential to industrial production:

Batch Mixing Systems: Laboratory stirred vessel (250°C, 500 rpm, 1.8 kg batches) scales to industrial continuous-feed reactor systems:

- Twin-screw extruder: 100-500 kg/hour production rates
- Ribbon blender + heating system: 50-200 kg/batch with mechanical conveying
- Rotary kiln (modified, indirect heating): 1000+ kg/hour potential production[50]

Forming and Cooling: Aluminum mold manual placement scales to:

- Semi-automated conveyor systems with molding stations
- Pneumatic or hydraulic press-assisted molding (reducing extraction time)
- Controlled cooling chambers maintaining optimal temperature gradients

Projected Production Efficiency: Industrial implementation could achieve:

- Production rate: 2,000-5,000 bricks/day (single facility)
- Labor requirement: 8-12 workers (vs. 40-50 for conventional brick kilns)
- Capital investment: ₹40-60 lakh (vs. ₹1-2 crore for conventional brick unit)[51]
- Manufacturing cost: ₹0.50-0.70/brick at scale (vs. ₹0.55-0.85 estimated)

5.3.2 Feedstock Availability and Supply Chain

Plastic Waste Availability: India generates 56 lakh tonnes annually; current recycling captures only 10-12 lakh tonnes, leaving 44 lakh tonnes available for brick manufacturing. Single industrial facility (5,000 bricks/day) would consume:

- Annual production: 1.5-1.8 million bricks
- Plastic requirement: 690-830 tonnes/year (46% of brick volume)
- Utilization: Represents <0.15% of annual plastic waste generation

Supply is not a constraint; multiple facilities could operate without competition for feedstock [52].

Foundry Waste Sand Availability: 500,000-700,000 tonnes global utilization potential; regional foundry clusters in Maharashtra, Gujarat, Tamil Nadu generate local surpluses suitable for brick manufacturing.

Coal Boiler Ash Availability: India's coal-fired power generation produces 200-250 million tonnes annual ash; finding markets for 2-3% represents minimal demand against available supply[9].

5.3.3 Geographic Distribution Model

Optimal industrial implementation envisions distributed manufacturing:

Cluster 1 - Foundry Regions: Gujarat, Maharashtra foundry concentrations

- Feedstock: On-site WFS + regional plastic collection centers + coal ash from power plants
- Market: Regional construction demand + export potential to emerging markets
- Economics: Minimized feedstock transport; utilize local construction market

Cluster 2 - Waste Management Hubs: Major urban agglomerations (Delhi, Mumbai, Bangalore, Chennai)

- Feedstock: Concentrated plastic waste collection + imported WFS + ash
- Market: Urban construction demand; established distribution networks
- Economics: Direct access to market; waste collection infrastructure exists

Cluster 3 - Coal-Fired Power Plant Regions: Thermal power generation zones

- Feedstock: On-site coal ash + regional plastic/WFS sourcing
- Market: Industrial and regional construction
- Economics: Ash disposal cost elimination; long-term power plant partnerships

This distributed model avoids transportation bottlenecks, creates regional employment, and develops circular economy integration within existing industrial infrastructure [53].

5.4 Regulatory and Standards Framework

5.4.1 Indian Standards Compliance

Current IS 1077:1992 (Common Burnt Clay Brick Specification) applies primarily to conventional clay bricks. Composite eco-bricks exceed all applicable mechanical requirements (compressive strength, water absorption) but operate outside the thermal domain for which this standard was developed.

Recommendation: Development of supplementary specification—"IS XXXX-2026: Specification for Composite Eco-Bricks from Waste Plastic, Foundry Sand, and Boiler Ash"—establishing:

- Material composition ranges and proportions
- Manufacturing process requirements and quality control
- Physical and mechanical property requirements
- Thermal stability and application temperature limits
- Bonding system specifications (AAC adhesive compatibility)
- Environmental and lifecycle criteria

Such specification would provide regulatory clarity, ensure quality consistency, and facilitate market adoption [54].

5.4.2 Building Code Integration

Eco-bricks require explicit approval within building codes and design standards:

- **NBC (National Building Code of India) 2016:** Currently references IS 1077 for brick materials. Proposed amendment should recognize waste-derived alternatives meeting or exceeding mechanical requirements while acknowledging thermal constraints
- **State Building Codes:** Regional climatic variations (temperature extremes) should be considered in geographic applicability
- **Green Building Standards:** LEED, IGBC (Indian Green Building Council) should provide bonus points or certification credit for waste valorization approach [55]

5.5 Limitations and Future Research Directions

5.5.1 Current Study Limitations

1. **Limited Sample Size:** Testing conducted on 6-8 specimens per protocol. Future work should employ larger sample populations (30-50 specimens) to establish robust statistical distributions.
2. **Single Thermal Condition:** Material characterized at ambient outdoor temperatures. Accelerated aging studies (UV exposure, thermal cycling) would establish long-term durability in service.
3. **Simplified Bonding Tests:** Mortar bonding evaluation limited to qualitative assessment. Quantitative bond strength measurement via pulloff testing or slant shear testing would provide standardization[56].
4. **No Microstructural Analysis:** Scanning electron microscopy (SEM), X-ray computed tomography (XCT), and other microstructural characterization techniques would elucidate failure mechanisms and internal structure-property relationships.
5. **Limited Mix Optimization:** Research employed single 46:46:8 proportion. Systematic variation of plastic-to-aggregate ratio (30-60% plastic) and boiler ash substitution (0-15%) would identify true optimal composition.
6. **No Lifecycle Assessment:** Comprehensive cradle-to-grave environmental assessment per ISO 14044 methodology would quantify environmental benefits with rigor.

5.5.2 Recommended Future Research

Near-Term (1-2 years):

1. Microstructural characterization via SEM, XCT to elucidate mechanical mechanisms
2. Extended aging and durability testing (UV, thermal cycling, chemical resistance)
3. Systematic mix design optimization across material proportion ranges
4. Quantitative mortar bond strength measurement
5. Pilot-scale manufacturing demonstration at 100+ bricks/day production rate

Medium-Term (2-4 years):

1. Full lifecycle assessment per ISO 14044 with third-party verification
2. Economic feasibility study for industrial-scale implementation

3. Development of supplementary Indian Standard specification
4. Field trials in actual construction to validate long-term performance
5. Investigation of alternative waste streams (tire rubber, reclaimed asphalt, mining waste)

Long-Term (4+ years):

1. Industrial-scale manufacturing facility development and operation
2. Market penetration studies and adoption barriers analysis
3. Policy development for waste stream integration mandates
4. Thermal reinforcement strategies to extend operating temperature range
5. Integration with other waste valorization approaches (composite materials containing multiple waste types)

6. Conclusion

Composite eco-bricks derived from waste plastic, foundry sand, and boiler ash represent a transformative approach to sustainable construction materials. By simultaneously addressing three critical environmental challenges (plastic waste, foundry waste, coal ash disposal) through integration into a superior-performing construction product, this technology exemplifies circular economy principles and demonstrates technical proof that waste materials can generate value rather than burden.

The convergence of technical superiority (8.66 N/mm² compressive strength), environmental excellence (75% emission reduction), and economic advantage (85% cost reduction) establishes an exceptionally compelling case for rapid technology adoption and industrial implementation. Future research should focus on scaling, optimization, and integration into policy frameworks to maximize societal benefit and environmental impact.

India, with its combination of substantial construction demand, significant waste generation, and policy commitment to circular economy and sustainability, represents optimal market context for this technology. Rapid adoption could simultaneously address: (1) plastic waste crisis, (2) industrial waste valorization, (3) construction cost reduction, (4) carbon emissions mitigation, and (5) sustainable development advancement. This research contributes essential technical foundation enabling these multiple simultaneous benefits.

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