

Durability and Environmental Performance Testing of Eco-Friendly Construction Materials under Field Conditions

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Abstract: Eco-friendly construction materials are central to sustainable infrastructure, yet their long-term performance under real environmental exposure is still insufficiently validated. Laboratory experiments, while controlled and precise, fail to reproduce the complex interplay of variables—rainfall, UV radiation, humidity, temperature cycling, freeze–thaw effects, and biological degradation—that influence material stability in the field. This research investigates the durability and environmental behavior of four major sustainable materials: compressed stabilized earth blocks (CSEB), fly ash–based geopolymer concrete, recycled aggregate concrete, and natural fiber composites. Field exposure trials were conducted in humid tropical, arid, and temperate regions for 18–24 months. Measurements included structural degradation patterns, strength retention, moisture absorption, microstructural evolution through SEM, and leachate chemistry based on ASTM and ISO standards. Results indicate that geopolymer concrete demonstrates the highest resilience, while natural fiber composites and CSEB show climate-dependent degradation. Recycled aggregate concrete provides stable performance with moderate porosity-linked deterioration. Leachate analyses confirm environmental safety across all materials. The study contributes comprehensive, field-based evidence essential for sustainable construction codes, policy decisions, and industrial adoption.

Keywords: Eco-friendly Materials, Durability, Field Testing, Environmental Performance, Sustainable Construction

1. Introduction

Sustainable construction represents one of the most urgent global priorities as countries seek to reduce carbon emissions and minimize the environmental burden associated with traditional building materials. Portland cement alone contributes nearly 7–8 percent of global CO₂ emissions, while fired bricks require energy-intensive kilns and non-renewable clay extraction [1]. Such environmental pressures have accelerated interest in eco-friendly alternatives including geopolymer concrete, recycled aggregate concrete, stabilized earth blocks, and natural fiber composites. These materials promise reduced embodied energy, lower pollution, and integration with circular-economy principles. Yet despite their sustainable advantages, widespread adoption is hindered by uncertainty regarding long-term field performance. Builders, engineers and policymakers remain cautious because laboratory conditions controlled temperature, calibrated humidity, and accelerated testing rarely capture the unpredictable, multi-factorial stresses that materials must endure over decades. Wind-driven rain, thermal shock, wet–dry cycling, prolonged UV exposure, and biological colonization can produce degradation mechanisms not predicted in laboratory tests [2]. Field-based research therefore fills a crucial knowledge gap by validating material behavior under authentic climatic and environmental conditions. This study provides one of the most comprehensive multi-material, multi-climate field evaluations aimed at bridging the gap between experimental innovation and practical construction reliability.

2. Background and Research Need

The Eco-friendly materials have demonstrated encouraging mechanical and environmental performance in controlled studies. Geopolymer concrete shows high resistance to chemical attack and reduced carbon footprint

due to substitution of cement with industrial by-products such as fly ash or slag [5]. CSEB lowers emissions by eliminating firing processes, and natural fiber composites promote biodegradability and low embodied energy [7]. However, concerns remain. CSEB may erode under heavy rainfall or lose strength under freeze–thaw cycles; recycled aggregate concrete may suffer durability issues due to residual mortar on old aggregates, which increases porosity; natural fibers may absorb water and promote fungal growth in humid climates; and geopolymer concrete may exhibit variability depending on precursor chemistry and curing conditions [3]. Moreover, environmental performance—especially leachate risk, biodegradability, and surface runoff interaction—must be assessed to ensure these materials do not introduce ecological hazards. Comprehensive field trials can help identify:

- degradation mechanisms specific to each climate
- thresholds of environmental stress that influence performance
- necessary protective treatments
- time-dependent changes in microstructure
- long-term maintenance requirements

The research is essential for revising building codes, validating green certifications, and establishing performance-based sustainability standards.



Fig. 1 Eco Friendly Construction Materials Under Field Conditions

3. Materials Investigated

The Compressed Stabilized Earth Blocks (CSEB)

CSEB are produced using local soil, stabilizers such as lime or cement, and mechanical compaction. Their environmental advantages stem from low embodied energy and avoidance of kiln firing [4]. Yet their performance is highly sensitive to soil composition and moisture.

Fly Ash–Based Geopolymer Concrete

Geopolymer concrete uses aluminosilicate precursors activated by alkaline solutions. It significantly reduces CO₂ emissions and offers excellent resistance to chemical and thermal degradation [5].

Recycled Aggregate Concrete (RAC)

RAC incorporates aggregates recovered from demolished concrete structures. It reduces landfill waste and supports circular-economy goals [6]. However, recycled aggregates tend to have higher water absorption and microcracks, influencing durability.

Natural Fiber Composites

Produced using plant fibers (jute, hemp, sisal) embedded in biodegradable or low-impact matrices, these composites offer low density, renewability, and biodegradability [7].

4. Field Testing Methodology

The Field stations were installed in three distinct climate zones:

1. Humid tropical region – high rainfall, intense UV exposure, and biological growth.
2. Arid region – high temperature variation, low humidity, intense solar radiation.
3. Temperate region – freeze–thaw cycles, moderate rainfall, seasonal variations.

Testing Protocol

Samples were exposed for 18–24 months. Measurements included:

- Compressive strength retention: tested at 0, 6, 12, 18, 24 months
- Water absorption and capillary rise: quantified using ASTM C140
- Surface erosion depth: mapped via profilometry
- Crack propagation: analyzed using optical microscopy
- Microstructure: assessed via SEM imaging
- Leachate testing: conducted using ASTM C1308 and ISO 1920 standards [8]
- Biodegradation assessment: particularly for natural fiber composites
- Thermal cycling impact: monitored using embedded thermocouples

Data were recorded quarterly, allowing temporal analysis of deterioration pathways.

5. Durability Performance Analysis

Geopolymer Concrete

Geopolymer concrete demonstrated the highest durability across all climates. It retained over 90 percent of its original compressive strength after 24 months and exhibited minimal microcracking. The dense microstructure resisted water absorption, and SEM analysis confirmed minimal chemical alteration. Even under intense UV exposure and thermal variations, degradation remained negligible, supporting earlier findings regarding geopolymer resilience [5].

Compressed Stabilized Earth Blocks (CSEB)

CSEB showed highly climate-sensitive performance. In arid climates, they remained structurally stable, with strength loss below 10 percent. However, in humid tropical regions, erosion, swelling, and loss of surface

integrity were evident. Heavy rainfall caused washing of fine particles, and wet–dry cycling induced cracking. Freeze–thaw cycles in the temperate site resulted in substantial surface scaling. Stabilizer content significantly influenced outcomes, with higher lime/cement ratios improving resistance [4].

Recycled Aggregate Concrete (RAC)

RAC maintained stable mechanical performance, losing only 5–12 percent strength across sites. However, porosity-induced degradation manifested as surface roughness and microcracking. UV exposure produced surface shrinkage cracking more visibly than in geopolymer concrete. Despite these issues, structural reliability remained acceptable, supporting the material’s suitability for non-critical load-bearing applications [6].

Natural Fiber Composites

Natural fiber composites were the most vulnerable in high-humidity environments. Fungal colonization, fiber swelling, matrix softening, and gradual loss of stiffness were recorded. SEM imaging revealed fiber–matrix debonding after 12 months. However, in temperate climates, degradation remained moderate, and composites retained usable mechanical properties. Protective coatings significantly reduced moisture-induced decay [7].

6. Environmental Performance Evaluation

Leachate tests indicated negligible environmental hazards:

- Geopolymer concrete released minimal Na^+ and Si^{4+} ions, remaining within safe limits.
- RAC exhibited low leaching due to stable mineral-binding characteristics.
- CSEB leachate contained trace minerals but no harmful elements.
- Natural fiber composites decomposed biologically without harmful residues.

Additionally, life-cycle impact analysis affirmed a 30–70 percent reduction in embodied carbon relative to conventional materials [3].

7. Utility of the Research

This expanded field study provides:

- empirical evidence required for updating sustainable construction codes
- climate-specific performance guidelines
- durability benchmarking for manufacturers
- recommendations for protective treatments and improved formulations
- risk assessments for environmental safety and long-term viability

Such data support government agencies, architects, builders, and developers seeking to transition from high-carbon materials toward sustainable construction systems.

8. Conclusion

Eco-friendly materials provide credible, sustainable alternatives to conventional construction products, but performance varies under real climatic stressors. Geopolymer concrete consistently outperformed others, whereas CSEB and natural fiber composites require region-specific design considerations and protective enhancements. Recycled aggregate concrete remains structurally reliable with moderate deterioration. This study delivers a comprehensive foundation for making informed, climate-appropriate decisions about integrating green materials into long-term construction practices.

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