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Development and Performance Evaluation of Waste-Derived Sustainable Construction Materials for High-Performance Infrastructure

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Abstract: The rapid increase in infrastructure development and urbanization has resulted in excessive consumption of natural construction materials and increased environmental pollution due to industrial and agricultural waste generation. The present study focuses on the development and performance evaluation of waste-derived sustainable construction materials (SCMs) for high-performance infrastructure applications. Industrial and agro-based wastes such as Fly Ash (FA), Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBS), and Multi-Layer Plastic Waste (MLP) were utilized as partial replacement materials in concrete composites to enhance sustainability and reduce environmental impact. The experimental investigation included material characterization, mix design preparation, specimen casting, curing, and testing of mechanical and durability properties. Different replacement levels of 5%, 10%, and 15% were investigated to identify the optimum sustainable mix proportion. Mechanical properties including compressive strength, split tensile strength, and flexural strength were evaluated along with durability parameters such as water absorption, permeability, and abrasion resistance. The results indicated that the incorporation of FA, RHA, and GGBS significantly improved the compressive strength and durability performance of concrete due to enhanced pozzolanic reactions and microstructural densification. Plastic waste addition improved lightweight characteristics and thermal insulation properties at optimized replacement levels. The optimum SCM mix exhibited superior mechanical performance and reduced permeability compared to conventional concrete. Furthermore, Life Cycle Assessment (LCA) demonstrated a significant reduction in CO_2 emissions, energy consumption, and landfill disposal burden. The study concludes that waste-derived sustainable construction materials provide an environmentally friendly and economically viable solution for sustainable infrastructure development. The research supports circular economy principles by integrating waste management with construction engineering for the development of eco-friendly and high-performance construction materials.
Keywords: Fly Ash; Green Concrete; Ground Granulated Blast Furnace Slag (GGBS); Life Cycle Assessment; Rice Husk Ash; Sustainable Construction Materials; Waste-Derived Materials.

I. INTRODUCTION

The construction industry plays a significant role in economic growth and infrastructure development; however, it is also one of the largest contributors to environmental degradation and depletion of natural resources. Rapid urbanization and population growth have increased the demand for construction materials such as cement, sand, and aggregates, leading to excessive extraction of natural resources. Cement manufacturing is highly energy-intensive and contributes significantly to greenhouse gas emissions. Globally, the construction sector contributes approximately 39% of carbon dioxide emissions and nearly 36% of energy consumption. Simultaneously, large quantities of industrial, agricultural, and plastic wastes are generated annually, causing severe environmental and disposal challenges. Fly ash generated from thermal power plants, rice husk ash from agricultural processing industries, GGBS from steel industries, and multi-layer plastic waste are commonly disposed of in landfills, resulting in environmental pollution and loss of valuable land resources. Utilization of these waste materials in construction applications offers a sustainable solution by integrating waste management with construction engineering. Sustainable Construction Materials (SCMs) have emerged as an effective alternative to conventional construction materials due to their environmental and economic benefits. SCMs improve the mechanical and durability characteristics of concrete while reducing cement consumption and carbon emissions. Previous studies have investigated individual waste materials such as fly ash, rice husk ash, and GGBS separately; however, limited research has focused on hybrid multi-material systems incorporating industrial, agricultural, and plastic wastes together in a single concrete composite.

Furthermore, limited studies have evaluated the long-term durability, environmental sustainability, and practical field applicability of waste-derived construction materials. Therefore, there is a need for comprehensive research integrating multiple waste materials and evaluating their mechanical, durability, environmental, and economic performance for sustainable infrastructure applications.

The present study aims to develop and evaluate waste-derived sustainable construction materials using Fly Ash (FA), Rice Husk Ash (RHA), Ground Granulated Blast Furnace Slag (GGBS), and Multi-Layer Plastic Waste (MLP) for high-performance infrastructure applications. The study includes experimental evaluation of strength and durability properties along with Life Cycle Assessment (LCA) and cost analysis for sustainability assessment.

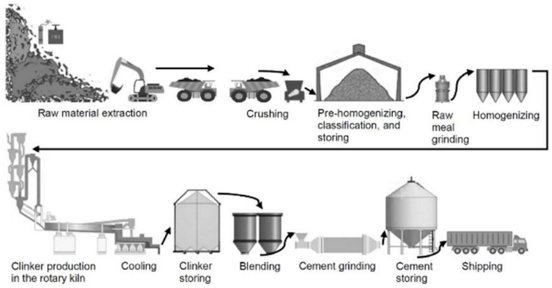


Figure 1. Environmental Impact of Conventional Construction Industry

II. MATERIALS AND METHODS

A. Materials Used

The materials used in the present investigation included Ordinary Portland Cement (OPC 53 Grade), fine aggregates, coarse aggregates, fly ash, rice husk ash, GGBS, and multi-layer plastic waste.

1) Cement: Ordinary Portland Cement (OPC 53 Grade) conforming to IS 12269:2013 was used as the primary binding material.
2) Fly Ash (FA): Class F Fly Ash obtained from a nearby thermal power plant was used as a supplementary cementitious material due to its pozzolanic properties.
3) Rice Husk Ash (RHA): Rice Husk Ash was collected from rice processing industries and processed through controlled burning and sieving to improve silica reactivity.
4) Ground Granulated Blast Furnace Slag (GGBS): GGBS collected from steel industries was used as a partial cement replacement material to improve long-term durability and strength.
5) Plastic Waste: Multi-layer plastic waste (MLP) was shredded and utilized as a lightweight replacement material.
6) Fine and Coarse Aggregates: Natural river sand and crushed stone aggregates conforming to IS 383:2016 were used.

B. Material Characterization

The physical and chemical properties of the materials were evaluated using standard laboratory procedures. Parameters such as specific gravity, fineness, particle size distribution, and chemical composition were determined.

Table 1. Physical Properties of Materials

Material	Specific Gravity	Fineness (%)
Cement	3.15	5
Fly Ash	2.25	8
RHA	2.10	12
GGBS	2.85	6
Plastic Waste	1.15	-

C. Mix Design

Concrete mixes were prepared with different replacement levels of SCMs to determine the optimum sustainable mix.

Table 2. Concrete Mix Proportions

Mix ID	Fly Ash (%)	GGBS (%)	RHA (%)	Plastic Waste (%)
CM	0	0	0	0
SCM-5	5	5	5	2
SCM-10	10	10	10	5
SCM-15	15	15	15	8

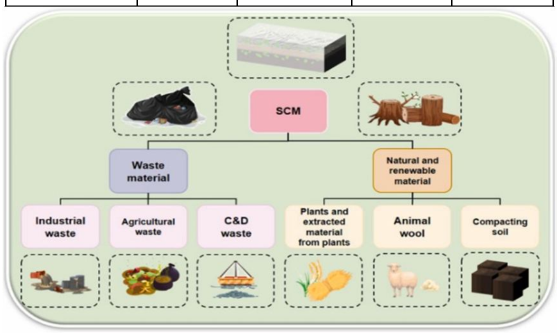


Figure 2. Classification of Waste-Derived Sustainable Construction Materials

D. Experimental Procedure

The experimental investigation included:

1) Material collection and processing
2) Material characterization
3) Concrete mix preparation
4) Specimen casting and curing
5) Mechanical property evaluation
6) Durability testing
7) Sustainability assessment

Concrete cubes, cylinders, and beams were cast and cured for 7, 14, and 28 days before testing.

Raw Material Collection
↓
Material Processing
↓
Mix Design Preparation
↓
Concrete Mixing
↓
Specimen Casting
↓
Curing
↓
Mechanical Testing
↓
Durability Analysis
↓
LCA Assessment

Figure 8. Experimental Methodology Flowchart

E. Testing Methods

Mechanical Tests

- Compressive Strength Test
- Split Tensile Strength Test
- Flexural Strength Test

Durability Tests

- Water Absorption Test
- Permeability Test
- Abrasion Resistance Test

All tests were conducted according to IS and ASTM standard procedures.

Figure 9. Concrete Specimen Casting and Curing

III. RESULTS AND DISCUSSION

A. Compressive Strength

The compressive strength of SCM concrete increased significantly with the incorporation of FA, RHA, and GGBS due to enhanced pozzolanic activity and microstructural densification.

Table 3. Compressive Strength Results

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
CM	24.5	31.2	38.4
SCM-5	26.8	34.6	42.5
SCM-10	28.5	37.8	46.2
SCM-15	27.2	35.5	43.6

The SCM-10 mix exhibited the highest compressive strength due to optimum interaction among supplementary cementitious materials.

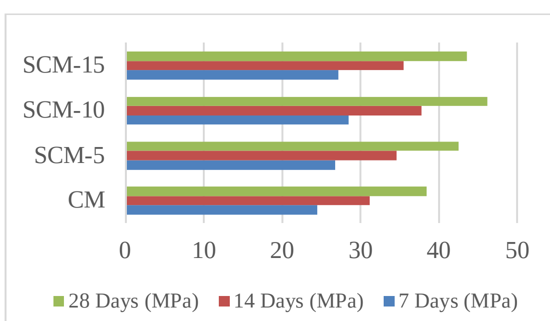


Figure 1. Comparative compressive strength performance of SCM concrete mixes at different curing ages.

B. Split Tensile Strength

The incorporation of SCMs improved tensile strength due to enhanced bonding characteristics and improved hydration reactions.

Table 4. Split Tensile Strength

Mix ID	Split Tensile Strength (MPa)
CM	3.25
SCM-5	3.65
SCM-10	4.10
SCM-15	3.88

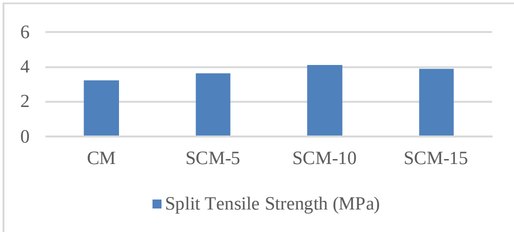


Figure 3. Split Tensile Strength Comparison of Sustainable Concrete Mixes

C. Flexural Strength

The addition of SCMs improved flexural strength due to improved particle packing and reduced microcracks.

Table 5. Flexural Strength Results

Mix ID	Flexural Strength (MPa)
CM	4.8
SCM-5	5.4
SCM-10	6.2
SCM-15	5.7

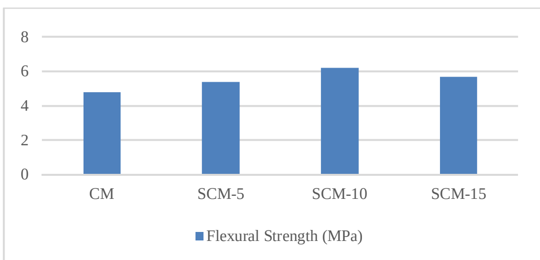


Figure 4. Flexural Strength Performance of SCM-Based Concrete

D. Durability Performance

1) Water Absorption

The water absorption of SCM concrete reduced significantly due to improved pore refinement and densification.

Table 6. Water Absorption Results

Mix ID	Water Absorption (%)
CM	5.8
SCM-5	4.6
SCM-10	3.8
SCM-15	4.1

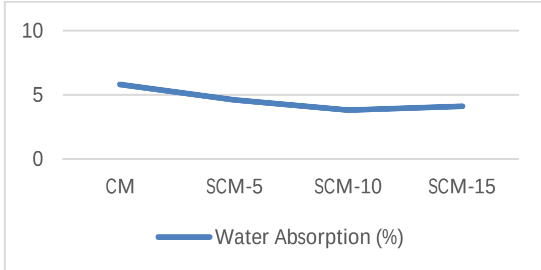


Figure 5. Water Absorption Reduction in SCM Concrete

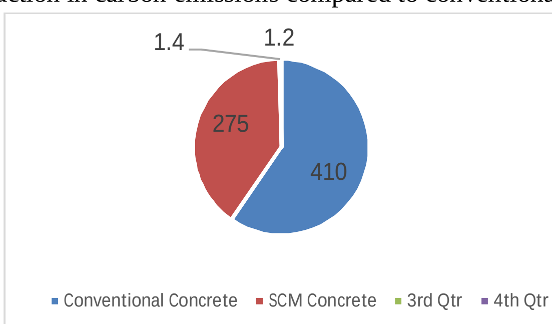
E. Sustainability Assessment

The Life Cycle Assessment (LCA) demonstrated significant environmental benefits due to reduced cement consumption and waste utilization.

Table 7. Environmental Benefits of SCM Concrete

Parameter	Conventional Concrete	SCM Concrete
CO_2 Emission (kg/m^3)	410	275
Energy Consumption (MJ/m^3)	3200	2250
Waste Utilization (%)	0	35

The study indicated nearly 33–40% reduction in carbon emissions compared to conventional concrete.



IV. DISCUSSION

The improved mechanical and durability performance of SCM concrete is mainly attributed to the pozzolanic reaction between supplementary cementitious materials and calcium hydroxide generated during cement hydration. The incorporation of Fly Ash, Rice Husk Ash, and GGBS improved the formation of calcium silicate hydrate (C-S-H) gel, resulting in enhanced microstructural densification and reduced permeability.

The optimum replacement level was observed in SCM-10 due to balanced material interaction and improved particle packing. Higher replacement levels slightly reduced strength due to reduced cementitious binding efficiency.

Plastic waste incorporation improved lightweight characteristics and thermal resistance while supporting waste management and circular economy principles. The reduction in water absorption indicates improved durability and reduced pore connectivity.

The environmental assessment confirmed that SCM concrete significantly reduces carbon emissions and energy consumption due to reduced cement usage and effective waste utilization. Therefore, waste-derived sustainable construction materials can be effectively utilized for sustainable and high-performance infrastructure development.

V. CONCLUSION

The present study investigated the development and performance evaluation of waste-derived sustainable construction materials for high-performance infrastructure applications. The incorporation of Fly Ash, Rice Husk Ash, GGBS, and plastic waste significantly improved the mechanical and durability properties of concrete while reducing environmental impact.

The SCM-10 mix exhibited optimum performance with maximum compressive, tensile, and flexural strength along with reduced water absorption and improved durability. The Life Cycle Assessment confirmed significant reductions in carbon emissions and energy consumption.

The research demonstrates that waste-derived sustainable construction materials provide an environmentally sustainable, economically feasible, and technically efficient solution for modern infrastructure development. The study supports circular economy principles by integrating waste management with sustainable construction engineering.

VI. FUTURE SCOPE

1) AI-based optimization of sustainable concrete mixes
2) Nano-material integration for enhanced performance
3) Geopolymer-based sustainable construction materials
4) Field-scale implementation studies
5) Smart self-healing concrete systems
6) IoT-based durability monitoring systems

VII. ACKNOWLEDGEMENT

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Conflict Of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

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