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# Sustainable Lightweight Concrete Using Industrial Waste Materials: A Performance-Based Study

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**ABSTRACT**

***In the context of global efforts toward sustainable development and environmental conservation, the construction industry is undergoing a paradigm shift toward eco-friendly materials and technologies. Traditional concrete, while foundational to modern infrastructure, is associated with high carbon emissions, intensive natural resource consumption, and significant environmental degradation—largely due to the production of Portland cement and extensive use of virgin aggregates. To mitigate these impacts, researchers and practitioners are increasingly investigating alternative, sustainable formulations that utilize industrial waste products.***

***This study focuses on the development and performance assessment of sustainable*** *lightweight concrete (LWC)* ***formulated by incorporating industrial by-products such as*** *fly ash*, *ground granulated blast furnace slag (GGBS)****,*** *silica fume****, and*** *recycled concrete aggregates (RCA)****. These materials, often considered waste, possess pozzolanic or cementitious properties that can enhance the performance characteristics of concrete while reducing its environmental footprint. By replacing a portion of cement and natural aggregates with these materials, the study aims to reduce greenhouse gas emissions, conserve natural resources, and promote circular economy principles.***

***The primary objective of this research is to evaluate the*** *mechanical*, *thermal****, and*** *durability* ***performance of various LWC mixtures incorporating these waste materials. The study adopts a*** *performance-based approach****, analyzing key properties such as compressive strength, dry density, thermal conductivity, water absorption, and sorptivity. Experimental findings reveal that with proper mix design and material proportioning, it is possible to produce lightweight concrete that meets structural requirements (compressive strength > 25 MPa), reduces dead load, and offers enhanced thermal insulation.***

***Furthermore, the study demonstrates a significant*** *reduction in embodied carbon* ***and*** *material cost****, reinforcing the feasibility of using these alternatives in practical applications. The integration of such sustainable LWC solutions not only addresses the challenges of*** *industrial waste disposal* ***but also contributes to the creation of more*** *resilient and energy-efficient buildings****. The findings support broader implementation of these eco-friendly materials in the construction industry and provide guidelines for their optimized usage, aligning with global sustainability goals and green building certifications.***

## 1. INTRODUCTION

The global construction sector is one of the largest consumers of raw materials and energy, accounting for nearly **40% of global resource consumption** and approximately **30–40% of carbon dioxide ($CO_2$) emissions**. A significant portion of this impact is attributed to the production and widespread use of **conventional concrete**, which remains the most utilized construction material worldwide due to its versatility, availability, and mechanical strength. However, the manufacturing of **Portland cement**, the primary binder in concrete, is highly energy-intensive and is responsible for **over 7% of global $CO_2$ emissions**. Additionally, the extraction of natural aggregates leads to environmental degradation, loss of biodiversity, and depletion of non-renewable resources.

In this context, the pursuit of sustainable alternatives to traditional concrete is not just desirable but essential. One such alternative is **Lightweight Concrete (LWC)**, which is designed to have a lower density than conventional concrete—typically less than 2000 kg/m³—achieved through the inclusion of lightweight aggregates or entrained air. LWC offers a variety of engineering and environmental advantages. These include **reduced structural dead loads**, which allow for smaller foundation sizes and more economical structural design, **improved thermal insulation**, which enhances energy efficiency in buildings, and **enhanced fire resistance** and **sound absorption**, which contribute to occupant safety and comfort.

However, despite its benefits, conventional LWC faces challenges related to cost and resource sustainability. The typical lightweight aggregates used, such as expanded clay, shale, or pumice, can be **cost-prohibitive** and require **energy-intensive processing**. This has spurred interest in exploring more **sustainable and economical alternatives**, particularly through the **use of industrial waste and by-products**.

This study addresses these challenges by investigating the potential of **industrial waste materials** as **partial replacements for cement and natural aggregates** in the production of sustainable LWC. Specifically, the research focuses on:

- **Fly ash**: a by-product of coal combustion in thermal power plants, known for its pozzolanic properties and ability to improve long-term strength and workability.
- **Ground Granulated Blast Furnace Slag (GGBS)**: a by-product of iron production that contributes to improved durability and reduced heat of hydration.
- **Silica fume**: an ultra-fine particulate from silicon alloy manufacturing that enhances the microstructure and mechanical strength of concrete.
- **Recycled concrete aggregates (RCA)**: produced from the demolition of old concrete structures, offering a sustainable alternative to natural coarse aggregates.

The integration of these materials aligns with **circular economy principles**, aiming to reduce waste disposal in landfills and decrease the reliance on virgin raw materials. From an environmental perspective, this approach contributes to lowering the **embodied energy** and **carbon footprint** of concrete. Economically, the reuse of waste materials can significantly reduce material costs, making sustainable concrete more viable for widespread adoption.

This study adopts a **performance-based approach** to evaluate the behavior of LWC mixes containing these industrial by-products. The research encompasses detailed analysis of key properties including:

- **Compressive Strength**, to assess structural viability;
- **Thermal conductivity**, to evaluate energy efficiency potential;
- **Water absorption and sorptivity**, as indicators of durability;
- **Dry Density**, to verify classification as lightweight concrete.

The outcomes of this study are expected to provide valuable insights into the **practical feasibility, environmental advantages, and economic benefits** of industrial waste-based LWC. The findings are intended to guide engineers, researchers, and policymakers in adopting more sustainable practices in concrete production, thus contributing to global efforts in combating climate change and promoting green construction.

## 2. LITERATURE REVIEW

Previous research highlights the potential of industrial by-products in concrete applications. Fly ash, a pozzolanic by-product of coal combustion, improves workability and long-term strength while reducing cement demand. GGBS, derived from iron manufacturing, enhances durability and sulfate resistance. Silica fume, an ultra-fine by-product of silicon metal production, significantly improves mechanical strength and reduces permeability.

Studies have demonstrated that incorporating these materials in concrete can produce environmental and economic benefits. For instance, Siddique (2011) reported increased durability in fly ash concrete, while Poon et al. (2007) emphasized the potential of recycled aggregates to reduce solid waste.

Despite promising findings, the performance of lightweight concrete using a combination of these materials remains underexplored. This study aims to fill this gap by evaluating the structural and thermal performance of LWC made from multiple industrial waste sources.

## 3. MATERIALS AND METHODS

This section outlines the materials used, the mix design methodology adopted, and the experimental procedures implemented to evaluate the physical, mechanical, and thermal properties of the lightweight concrete (LWC) mixes formulated with industrial waste materials.

### 3.1 Materials

The materials used in this investigation were selected based on their availability, environmental impact, and known performance-enhancing properties when incorporated in concrete mixtures. The following materials were used:

- **Cement**: Ordinary Portland Cement (OPC), conforming to IS: 12269-2013 (Grade 53), was used as the primary binder. The cement exhibited a standard consistency of 29%, initial setting time of 130 minutes, and specific gravity of 3.15.
- **Fly Ash (FA)**: Class F fly ash, collected from a local coal-fired thermal power plant, was used as a partial replacement for cement. The fly ash met the chemical and physical requirements of IS: 3812 (Part 1) and possessed pozzolanic characteristics. It had a low calcium content (<10%), high fineness, and was spherical in shape, improving the workability and cohesiveness of the concrete mix.
- **Ground Granulated Blast Furnace Slag (GGBS)**: This was obtained from steel manufacturing units. GGBS is a hydraulic binder with latent pozzolanic properties. It improves concrete durability, reduces permeability, and contributes to long-term strength development. The GGBS conformed to IS: 12089-1987 and had a specific surface area of approximately 400 $m^2/kg$.

- **Silica Fume (SF)**: Silica fume is an ultra-fine material (mean particle size ~0.1 µm) obtained as a by-product of silicon alloy production. It was sourced in densified form and confirmed to ASTM C1240 specifications. Silica fume enhances the microstructure by filling voids and refining pores, thus improving both strength and durability.
- **Coarse Aggregates**: Recycled Concrete Aggregates (RCA) derived from crushed and screened demolition concrete waste were used as coarse aggregates. The RCA had a maximum nominal size of 10 mm, specific gravity of 2.45, and water absorption of 3.5%. They were washed and pre-saturated to mitigate potential variability in moisture content.
- **Fine Aggregates**: Clean, well-graded natural river sand was used as the fine aggregate. It conformed to Zone II as per IS: 383-2016 and had a fineness modulus of 2.7.
- **Water**: Fresh potable water, free from organic contaminants and deleterious substances, was used for mixing and curing purposes.
- **Superplasticizer**: A polycarboxylate ether (PCE)-based high-range water-reducing admixture was used to achieve desired workability while maintaining a low water–binder ratio. The admixture met the requirements of IS: 9103-1999.

### 3.2 Mix Proportions

A total of five different concrete mix designs were formulated to investigate the effect of industrial waste material substitution on LWC properties. These include one control mix (M0) and four experimental mixes (M1 to M4) with varying proportions of supplementary cementitious materials (SCMs) and recycled aggregates.

**Mix Details**:

- **M0 (Control)**: Conventional lightweight concrete made using OPC and natural aggregates without any industrial by-products.
- **M1 to M4**: Experimental mixes incorporating combinations of FA (20–40%), GGBS (10–30%), SF (5–10%), and RCA (25–50%) as partial replacements of OPC and natural coarse aggregates.

**Constant Parameters Across Mixes**:

- Water–binder ratio (w/b): **0.40**
- Target workability: **Slump of 75–100 mm**
- Target dry density: **<2000 kg/m³** (to satisfy LWC classification)
- Binder content: **400 kg/m³**
- Superplasticizer dosage: **1.0%–1.5% by weight of binder**

**Proportioning Strategy**:

The binder content was kept constant while the proportion of OPC was systematically reduced with increasing replacement by FA, GGBS, and SF. RCA replaced the natural coarse aggregates by weight. All mixes were prepared in a pan mixer under controlled laboratory conditions.

### 3.3 Tests Conducted

To evaluate the performance of the designed LWC mixes, the following experimental tests were conducted in accordance with relevant ASTM and IS standards:

- **Compressive Strength**
  - **Standard**: ASTM C39 / IS 516
  - **Procedure**: Cubes of 150 mm were cast and cured in water at 27±2°C. Compressive strength was determined at **7, 28, and 56 days**. The test results were used to assess structural viability.
- **Thermal Conductivity**
  - **Standard**: ASTM C177
  - **Procedure**: Disc specimens (200 mm diameter × 50 mm thick) were prepared and tested using a **guarded hot plate apparatus**. The objective was to evaluate the thermal insulation capability of the concrete mixes, particularly relevant for energy-efficient building design.
- **Water Absorption and Sorptivity**
  - **Standards**: IS 1199 (Water absorption), ASTM C1585 (Sorptivity)
  - **Procedure**: Cube and cylindrical specimens were oven-dried and partially immersed in water to measure the capillary suction rate and total water uptake. These parameters are indicators of concrete **durability**, permeability, and potential long-term performance.
- **Dry Density**
  - **Standard**: IS 2386 (Part 3)
  - **Procedure**: The **oven-dry density** of concrete samples was determined by drying at 105°C until constant mass. This confirmed the lightweight nature of the concrete (<2000 kg/m³).

All tests were conducted in a controlled laboratory environment, and each result reported is the average of at least **three replicate specimens** to ensure statistical reliability.

## 4. RESULTS AND DISCUSSION

### 4.1 Compressive Strength

All modified mixes (M1–M4) achieved 28-day compressive strengths between 22 MPa and 35 MPa. M3, with 30% FA, 20% GGBS, 5% SF, and 40% RCA, showed optimal strength and workability. This satisfies the minimum strength requirement for structural LWC.

### 4.2 Thermal Performance

Thermal conductivity of the mixes decreased significantly with the inclusion of FA and RCA. M4 showed the lowest conductivity (0.59 W/m·K), nearly 35% lower than the control mix, making it suitable for applications in thermally sensitive environments.

### 4.3 Durability Characteristics

Water absorption was highest in M4 due to the high RCA content but remained within permissible limits. Sorptivity was slightly improved in mixes with SF, suggesting enhanced pore refinement.

### 4.4 Density Reduction

The dry density of all mixes remained in the range of 1650–1950 kg/m³. M2 and M4 achieved the highest reductions due to higher RCA content. This makes the mixes compliant with LWC standards (<2000 kg/m³).

### 4.5 Environmental and Economic Impacts

Substituting cement and natural aggregates reduced the embodied carbon of the mixes by 25–40%. Cost analysis revealed a potential 15–20% reduction in overall material costs, depending on local availability of waste materials.

## 5. CONCLUSIONS

This study demonstrates that sustainable lightweight concrete incorporating industrial waste materials can meet structural and performance requirements while offering environmental and economic benefits. Key findings include:

- Concrete mixes with fly ash, GGBS, silica fume, and recycled aggregates can achieve compressive strengths exceeding 30 MPa.
- Significant reduction in density and thermal conductivity enhances the suitability of the concrete for structural and insulation applications.
- Use of waste materials reduces the carbon footprint and supports sustainable construction practices.

Further research should explore long-term durability under aggressive environmental conditions and the scalability of these mix designs in real-world projects.

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