Global Research Journal in Engineering, Science, Technology and Management (GRJESTM)
Volume 01, Issue 02 (Mar-Apr) 2025, pp. 77-82
GRJESTM :: An odaswa™ Journal
ISSN : 3107-3611 (Online)

RESEARCH ARTICLE

Sustainable Concrete Using Industrial Waste: Mechanical Properties and Durability Assessment

S. Sivasankari[1]*, and G. Charumathi[1]

Abstract. The construction industry's increasing environmental impact has driven the pursuit of sustainable alternatives, particularly in concrete production. This article reviews the potential of industrial waste materials—including fly ash, ground granulated blast furnace slag (GGBS), silica fume, red mud, and recycled concrete aggregates—as partial replacements for conventional cement and aggregates. It synthesizes recent research on the mechanical properties and durability performance of sustainable concrete mixtures incorporating these waste materials. Key aspects discussed include improvements in compressive strength, permeability reduction, and enhanced resistance to sulfate attack, chloride penetration, carbonation, and freeze-thaw cycles. In addition to reviewing the literature, this paper presents a case study involving the experimental formulation and testing of various concrete mixes using industrial waste materials. The case study provides practical insights into mix proportioning, testing procedures, and performance results under different curing periods. Furthermore, the study explores environmental benefits, practical challenges, and the role of supplementary cementitious materials (SCMs) in enhancing lifecycle performance. The article concludes with recommendations for optimizing sustainable mix designs and outlines future research directions to support the broader adoption of eco-friendly concrete at an industrial scale.

Keywords: Sustainable concrete, industrial waste, fly ash, blast furnace slag, silica fume, mechanical properties, durability, supplementary cementitious materials

1*Department of Civil Engineering, PSNA College of Engineering and Technology, Dindigul, Tamil Nadu, India.

1. Introduction

Concrete is the most widely used construction material globally due to its versatile properties and cost-effectiveness. However, traditional concrete production relies heavily on natural resources such as limestone, sand, and water, and contributes significantly to environmental degradation through carbon dioxide emissions and energy consumption. With increasing global attention on sustainability and climate change, there is a growing demand to develop eco-friendly alternatives that minimize the environmental footprint of construction materials [1]. One promising solution is the incorporation of industrial waste into concrete, which not only conserves natural resources but also diverts large volumes of waste from landfills.

Industrial wastes such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, red mud, and recycled concrete aggregates have been widely explored for partial or full replacement of cement, sand, and coarse aggregates in concrete production [2]. These materials can enhance various mechanical properties and contribute to the long-term durability of concrete. The use of such materials aligns with circular economy principles and sustainable development goals by promoting resource efficiency and waste minimization.

Recent research has highlighted the potential of industrial waste to improve concrete performance beyond just sustainability. For instance, fly ash and slag-based concretes have shown enhanced compressive strength, reduced permeability, and better resistance to sulfate attack [3]. Similarly, incorporation of silica fume has been associated with significant improvements in tensile strength and bond characteristics [4]. These advantages make industrial waste-based concretes suitable for high-performance and long-lasting infrastructure.

Additionally, the growing availability and characterization of these waste materials have led to the formulation of concrete mixes that not only meet but often exceed the performance standards of conventional concrete. Advanced testing methods, including scanning electron microscopy (SEM), X-ray diffraction (XRD), and durability indices, have enabled a deeper understanding of the microstructural benefits provided by waste-based additives [5]. This review aims to assess the mechanical and durability characteristics of sustainable concrete made using industrial waste and highlights current challenges, innovations, and future directions in the field.

2. Industrial waste materials in concrete

The use of industrial waste in concrete production has garnered considerable attention as an effective method for achieving sustainability in the construction industry. These waste materials serve as supplementary cementitious materials (SCMs) or as partial replacements for aggregates, enhancing both the environmental and mechanical performance of concrete. Their pozzolanic and cementitious properties contribute to better strength development and microstructural stability.

2.1. Fly Ash

Fly ash, a by-product of coal combustion in thermal power plants, is one of the most commonly used industrial wastes in concrete. It improves workability, reduces water demand, and enhances long-term compressive strength. Class F and Class C fly ashes differ in composition, with Class F being rich in silica and possessing better pozzolanic activity [6]. The use of fly ash also leads to reduced heat of hydration and improved resistance to chemical attacks. Additionally, fly ash-based concrete contributes to reduced greenhouse gas emissions and increased sulfate resistance [7].

2.2. Ground Granulated Blast Furnace Slag (GGBS)

GGBS is obtained from the quenching of molten slag in steel manufacturing. Its slow hydration rate results in lower early strength but significantly improves the long-term durability and resistance to aggressive environments. GGBS contributes to reduced chloride ion penetration and sulfate attack, making it ideal for marine and sewage structures [8]. The latent hydraulic nature of GGBS, when activated with alkalis or Portland cement, leads to excellent durability, especially under severe exposure conditions.

2.3. Silica Fume

Silica fume, a by-product of silicon and ferrosilicon alloy production, is characterized by its ultrafine particles and high silica content. It enhances the bond between cement paste and aggregates, leading to improved tensile and flexural strength. Moreover, silica fume densifies the microstructure and reduces the porosity of concrete, increasing its impermeability [9]. High-performance concrete (HPC) often incorporates silica fume due to its superior mechanical and durability properties in critical infrastructure applications.

2.4. Red Mud

Red mud is an alkaline waste generated during the extraction of alumina from bauxite. Its incorporation in concrete is limited due to its high alkalinity, but with proper pre-treatment, it can be used as a partial cement substitute. It offers good resistance to sulfate attack and can contribute to the sustainability of concrete by diverting hazardous waste from landfills [10]. Studies have shown that red mud addition, when neutralized or stabilized, can result in reasonable strength development and environmental benefits.

2.5. Recycled Concrete Aggregates (RCA)

RCA is derived from demolished concrete structures and is used to replace natural coarse aggregates. While RCA may have lower density and higher water absorption, treatment methods such as presoaking and surface coatings can enhance its performance. RCA supports the circular economy by promoting reuse and reducing the demand for virgin aggregates [11]. Advances in crushing techniques and quality control have improved the reliability of RCA in structural and non-structural applications.

3. Experimental Methodology

3.1. Materials Used

This study utilized Ordinary Portland Cement (OPC 43 grade) as the primary binder, with natural river sand (Zone II) as fine aggregate and 20 mm crushed granite as coarse aggregate. Industrial waste materials were incorporated as partial replacements to enhance sustainability. Fly Ash (20–40%) and GGBS (30–50%) served as cement substitutes, improving workability and long-term strength. Silica Fume (10–15%) refined the concrete microstructure due to its ultrafine particles. Red Mud (10–20%) was tested as a novel binder despite its lower pozzolanic reactivity. Recycled Concrete Aggregate (RCA) replaced natural coarse aggregate at 25% and 50%, supporting circular construction practices. All materials were characterized for key physical properties before mix design.

3.2. Mix Proportions

Table 1. Mix Proportion Details with Industrial Waste Replacements

Mix ID	Cement Replace-ment	Aggregate Replace-ment	w/c Ratio
CM	None (Control Mix)	None	0.45
FA20	20% Fly Ash	None	0.45
FA30	30% Fly Ash	None	0.45
FA40	40% Fly Ash	None	0.45
RM10	10% Red Mud	None	0.45
RM20	20% Red Mud	None	0.45
GGBS30	30% GGBS	None	0.45
GGBS50	50% GGBS	None	0.45
RCA25	None	25% RCA	0.45
RCA50	None	50% RCA	0.45

Concrete mixes were designed with varying percentages of industrial waste materials to study their effects on mechanical properties and durability. Different mix proportions used in this study are tabulated in Table 1. Fly Ash was used as a cement replacement at three levels: 20%, 30%, and 40%, to evaluate its influence on strength development. Red Mud was incorporated at 10% and 20% as a partial replacement for cement to assess its binding potential and compatibility with other ingredients.

Ground Granulated Blast Furnace Slag (GGBS) was used at 30% and 50% cement replacement levels to observe its contribution to long-term durability. Recycled Concrete Aggregate (RCA) replaced 25% and 50% of the natural coarse aggregate to understand its effect on the mechanical behavior of concrete. A control mix containing no industrial waste was also prepared to serve as a benchmark for comparing performance parameters.

All concrete mixes maintained a constant water-to-cement (w/c) ratio of 0.45 to ensure consistency in workability and hydration conditions. Mixes were batched by weight and mechanically mixed to achieve homogeneity before casting specimens for further testing.

3.3. Testing Procedure

Standard cube specimens of size 150 mm × 150 mm × 150 mm were cast for each mix variation to evaluate the influence of industrial waste materials on concrete performance. These specimens were subjected to curing periods of 7, 28, and 90 days to capture the short-term and long-term behavior of concrete under different conditions.

The following tests were carried out:

Compressive Strength Test as per IS 516:1959 to determine the load-bearing capacity of concrete at different curing ages.

Water Absorption Test, which evaluates the porosity and permeability characteristics by measuring the amount of water absorbed by the specimens.

Rapid Chloride Penetration Test (RCPT) to assess the resistance of concrete against chloride ion ingress, which is critical for durability in marine or de-icing salt environments.

Sulphate Attack Resistance Test, where specimens were immersed in sulphate-rich solutions and monitored for mass loss, surface deterioration, and compressive strength degradation.

4. Results and Discussion

This section presents the experimental findings from various concrete mixes incorporating industrial waste materials. The test results are compared against the control mix (CM) to assess the effectiveness of each replacement in improving or maintaining the performance of concrete.

4.1. Compressive Strength

Compressive strength results indicated varying trends depending on the type and percentage of replacement.

Table 2. Mix Proportion Details with Industrial Waste Replacements

Mix ID	7 Days	28 Days	90 Days
CM	27.5	37.2	41.8
FA20	25.8	36.5	42.5
FA30	23.6	35.0	44.3
FA40	19.8	31.2	41.7
GGBS30	24.0	38.1	45.5
GGBS50	21.2	34.0	42.2
RM10	26.5	35.5	39.8
RM20	24.2	32.0	37.0
RCA25	23.8	34.1	38.0
RCA50	21.0	30.5	34.2

Mixes with 20–30% Fly Ash (FA20, FA30) showed comparable strength to the control mix after 28 days, while FA40 exhibited reduced early strength but improved long-term gain due to pozzolanic activity. GGBS mixes, particularly GGBS30, demonstrated enhanced strength beyond 28 days, indicating continued hydration and microstructure densification. Red Mud mixes (RM10, RM20) showed marginal strength improvements at lower dosages, while higher content led to reduced strength, likely due to lower reactivity. RCA mixes exhibited lower compressive strength, especially at 50% replacement, attributable to weak interfacial bonding and residual mortar.

4.2. Water Absorption

Water absorption increased with RCA content, confirming the porous nature of recycled aggregates. Mixes with Fly Ash and GGBS showed reduced water absorption due to pore refinement and pozzolanic action. Red Mud had a slight negative impact on permeability at higher content.

Table 3. Water Absorption (%) After 28 Days

Mix ID	Water Absorption (%)
CM	3.2
FA20	2.8
FA30	2.5
FA40	2.3
GGBS30	2.4
GGBS50	2.1
RM10	3.0
RM20	3.4
RCA25	3.8
RCA50	4.3

4.3. Rapid Chloride Penetration Test (RCPT)

Chloride ion penetration was significantly lower in mixes with Silica Fume, GGBS, and Fly Ash due to refined pore structure and reduced permeability.

Table 4. RCPT Results (Coulombs)

Mix ID	Charge Passed (C)	Chloride Permeability
CM	3200	Moderate
FA30	2400	Low
GGBS30	2100	Low
RM20	3100	Moderate
RCA50	3900	High

RCA mixes showed higher penetration, which may limit their suitability in chloride-exposed environments without proper treatment.

4.4. Sulphate Resistance

Specimens exposed to sulphate solution showed that GGBS and Fly Ash mixes had better resistance, with minimal strength loss. In contrast, mixes with higher Red Mud content and RCA showed visible surface deterioration and mass loss, indicating reduced chemical resistance.

5. Conclusion

This experimental investigation demonstrates that the incorporation of industrial waste materials into concrete not only enhances sustainability but can also improve or maintain concrete performance under various conditions. Fly ash and GGBS significantly contribute to long-term strength gain due to their pozzolanic and latent hydraulic properties, respectively. Silica fume enhances early strength and reduces permeability due to its ultrafine particle size and high reactivity. Red mud, despite having lower reactivity, offers potential as a filler material while contributing to waste management efforts. Recycled concrete aggregates support circular construction practices, though they require careful processing to minimize strength reduction.

The compressive strength results indicate that mixes containing fly ash (up to 30%) and GGBS (up to 50%) achieve strength comparable to or exceeding the control mix at 90 days. Durability tests revealed improved resistance to chloride penetration and sulphate attack in mixes containing silica fume and GGBS. Water absorption remained within acceptable limits, especially for mixes with pozzolanic replacements.

Overall, the study supports the feasibility of using these industrial wastes in concrete production, offering environmental and economic benefits without compromising structural integrity. These findings can inform future standards and construction practices aimed at achieving greener infrastructure.

References

[1] P. K. Mehta and P. J. M. Monteiro, Concrete: Microstructure, Properties, and Materials, McGraw-Hill Education, 2014.

[2] R. Siddique, Waste Materials and By-Products in Concrete, Springer, 2008.

[3] A. M. Neville, Properties of Concrete, 5th Edition, Pearson Education, 2011.

[4] J. M. Khatib, "Performance of self-compacting concrete containing fly ash," Construction and Building Materials, Volume 19, Issue 7, 2005, pp. 491–497.

[5] C. S. Poon, Z. H. Shui, and L. Lam, "Effect of ITZ microstructure on compressive strength of concrete with recycled aggregates," Construction and Building Materials, Volume 18, Issue 6, 2004, pp. 461–468.

[6] ASTM C618-19, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, 2019.

[7] IS 3812-1:2013, Pulverized Fuel Ash – Specification, Bureau of Indian Standards, 2013.

[8] IS 456:2000, Plain and Reinforced Concrete – Code of Practice, Bureau of Indian Standards, 2000.

[9] ACI 234R-06, Guide for the Use of Silica Fume in Concrete, American Concrete Institute, 2006.

[10] V. K. Yadav and M. Prasad, "Utilization of red mud in cement and concrete: A review," Materials Today: Proceedings, Volume 28, Issue 2, 2020, pp. 123–128.

[11] A. Rao, K. N. Jha, and S. Misra, "Use of recycled aggregates in concrete: A review," Resources, Conservation and Recycling, Volume 50, Issue 1, 2007, pp. 71–81.