

Mechanical and Environmental Assessment of Sustainable Concrete Containing Limestone Waste and Fly Ash

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ABSTRACT

In this study the rapid increase in construction activities has led to excessive consumption of natural resources and the generation of large volumes of industrial and mining waste. In the pursuit of sustainable construction practices, this study investigates the mechanical performance of concrete incorporating limestone waste as a partial replacement for coarse aggregate and fly ash as a supplementary cementitious material. This study investigates the mechanical and environmental performance of concrete incorporating limestone waste and fly ash as partial replacements for cement and fine aggregate. Fly ash, a pozzolanic by-product of coal combustion, and limestone waste, derived from stone processing industries, were used to reduce the reliance on traditional cement and natural aggregates, thus lowering the environmental footprint. The primary objective is to reduce the environmental impact of conventional concrete by utilizing waste materials without compromising strength and durability.

Concrete mixes were designed with varying proportions of fly ash (10%, 20%, and 30%) and limestone waste (10%, 20%, and 30%) by weight. The mechanical properties evaluated include compressive strength, split tensile strength, and flexural strength at 7, 28, and 60 days. Additionally, durability aspects such as water absorption and resistance to acid attack were assessed. Environmental performance was analyzed through a simplified life-cycle assessment (LCA), focusing on CO₂ emissions and resource conservation. The results indicated that the inclusion of limestone waste and fly ash improves the workability and long-term strength of concrete, with optimal performance observed at 20% limestone waste replacement.

This study highlights the dual benefits of improving mechanical performance and reducing environmental impacts, positioning fly ash and limestone waste as effective components in green concrete technology. The findings support the potential of such waste-integrated concrete in general construction applications, paving the way for more eco-friendly building practices.

Keywords: Sustainable Concrete, Limestone Waste, Fly Ash, Supplementary Cementitious Materials (SCMs), Waste Utilization

1.INTRODUCTION

The construction industry is one of the largest consumers of natural resources and a major contributor to environmental pollution. Conventional concrete production relies heavily on cement and natural aggregates, both of which involve energy-intensive processes and the depletion of non-renewable resources. Additionally, the cement industry accounts for a significant portion of global carbon dioxide (CO₂) emissions, further exacerbating climate change. In response to these environmental challenges, the need for sustainable construction practices has become increasingly urgent. One of the most promising approaches to sustainable construction is the utilization of industrial and mining waste in concrete production. This not only helps in conserving natural resources but also offers a practical solution to the growing problem of waste disposal. Fly ash, a by-product of coal combustion in thermal power plants, is a widely used supplementary cementitious material known for its pozzolanic properties. It enhances the durability and long-term strength of concrete while reducing the overall cement content. Similarly, limestone waste, generated in large

quantities during the cutting and processing of dimensional limestone, represents a valuable yet underutilized resource. When used as a partial replacement for natural coarse aggregates, limestone waste can reduce the environmental footprint of concrete and contribute to circular economy principles in the construction sector.

This study focuses on the mechanical evaluation of sustainable concrete containing both limestone waste and fly ash. The objective is to assess how these materials influence the mechanical properties of concrete, including compressive strength, split tensile strength, and flexural strength, at various curing periods. By analyzing the performance of such modified concrete mixes, the research aims to support the development of eco-friendly alternatives to conventional concrete that do not compromise structural integrity.

2.LITERATURE REVIEW

N. Bheel, et.al (2020)- The aim of this study is to evaluate the properties of fresh and hardened concrete by partially replacing cement with sugarcane bagasse ash (SCBA) and limestone fines (LSF). In this investigation work the cement was replaced with SCBA ash and LSF by 0% (0% SCBA+ 0% LSF), 5% (2.5% SCBA+ 2.5% LSF), 10% (5% SCBA+ 5% LSF), 15% (7.5% SCBA+ 7.5% LSF) and 20% (10% SCBA+ 10% LSF) by weight of cement. In this regard, a total of 60 samples of concrete specimens were made with mix proportion of 1:1.5:3 with 0.56 water-cement ratio. Cube specimens were tested for compressive strength and cylindrical specimens were used for determining splitting tensile strength at 7 and 28 days respectively. The optimum result displayed that the crushing strength and split tensile strength increased by 10.33% and 10.10% while using 5% SCBA+ 5% LSF as a substitute for cement in concrete after the 28th day.

Saloni et al (2021)- This study examines the use of waste marble aggregates (WMA) as a substitute to natural aggregates (NA) to produce sustainable alkali activated concrete (AAC). Sodium hydroxide (NaOH) of 8M concentration and sodium silicate (Na_2SiO_3) were used as an alkaline activator for high calcium fly ash based AAC. NA were replaced with WMA at different weight ratios, namely 0%, 25%, 50%, 75% and 100%. Different properties like density, workability, air content, compressive, flexural and tensile strengths, along with modulus of elasticity of fresh and hardened concrete were investigated. The outcomes of this study revealed that WMA can be employed to replace up to 50% of NA in the production of sustainable AAC. Its high potential to replace NA could lead to significant saving in energy, cost and, can further reduce the hazardous environmental impacts caused by marble industries during mining, processing and polishing phases.

Kennedy C. Onyelowe et al. (2022)- This research work is a multi-objective exercise. Intelligent models are proposed for multiple concrete mixes utilizing FA as a replacement for cement to predict 28-day concrete compressive strength and life cycle assessment (LCA) for cement with FA. The data collected show that the concrete mixes with a higher amount of FA had a lesser impact on the environment, while the environmental impact was higher for those mixes with a higher amount of cement. The models which utilized the learning abilities of ANN (-BP, -GRG, and -GA), GP and EPR showed great speed and robustness with R2 performance indices (SSE) of 0.986 (5.1), 0.983 (5.8), 0.974 (7.0), 0.78 (19.1), and 0.957 (10.1) for Fc, respectively, and 0.994 (2.2), 0.999 (0.8), 0.999 (1.0), 0.999 (0.8), and 1.00 (0.4) for P, respectively. Overall, this shows that ANN-BP outclassed the rest in performance in predicting Fc, while EPR outclassed the others in predicting P. Relative importance analyses conducted on the constituent materials showed that FA had relatively good importance in the concrete mixes.

JoseNeves et al. (2023) - This work evaluates the mechanical performance of asphalt mixtures that include SSA in their composition. Asphalt mixtures were evaluated through laboratory tests for affinity between binder and aggregate, Marshall and volumetric properties, stiffness, resistance to fatigue, permanent deformation, and water sensitivity. Two rates of SSA incorporation—20% and 35%—were considered. In general, results indicated that incorporating SSA has not impaired the behavior of the asphalt mixtures. In some cases, the presence of SSA has improved mechanical performance. It was the case of the resistance to permanent deformation, stability, flow, and water sensitivity. This work confirms the suitability of the SSA application in asphalt mixtures beyond the benefit of promoting industrial waste in pavement engineering.

J. Thorne, D.V. Bompa et. al (2024)- This work examines the environmental impact of low-carbon concrete that incorporates supplementary cementitious materials (SCMs). After reviewing near-zero carbon SCMs and low-carbon concrete, a life cycle assessment (LCA) was undertaken for concrete mix designs with normal-to-high compressive strengths, incorporating limestone and fly ash as cement replacements. The analysis includes relevant region-specific life cycle inventory parameters for raw materials, energy production, and transportation. The results of this paper indicate that incorporating limestone and fly ash in concrete can reduce carbon emissions, yet at a proportional decrease in mechanical properties compared to conventional cement concrete.

Mohammad Tosif Chhipa et al. (2025) - The most frequently used building material on this planet is concrete. Concrete is the supreme user of natural resources as a result of its widespread use as construction material. Cement production produces significant amount of greenhouse emissions. The protection of environment has become challenging in many developing countries, 7-8% of CO₂ is produced by the cement industry that causes huge damage to the environment. In concrete production, and limestone can be a partial alternative to cement. The limestone waste is transported and disposed in landfills. The cement was replaced by limestone waste in the ratio of 25% to 30% in concrete by limiting the waste of limestone in the concrete, cement content can be reduced, which turns into an eco-friendly solution.

3. METHODOLOGY

This study investigates the mechanical properties of sustainable concrete incorporating limestone waste and fly ash as partial replacements for cement and fine aggregate. The methodology outlines the material selection, mix design, sample preparation, curing, testing, and analysis procedures.

Material Selection:

Cement-

- ✚ Ordinary Portland Cement (OPC) 43/53 grade conforming to IS 12269.
- ✚ Used as the primary binder.

Fly Ash -

- ✚ Class F fly ash sourced from a thermal power plant.
- ✚ Used as a partial replacement for cement (by weight) at varying percentages (e.g., 10%, 20%, 30%).

Limestone Waste -

- ✚ Collected from marble processing industries or quarrying operations.
- ✚ Ground to fine powder or used as fine aggregate replacement.
- ✚ Replacement levels: 10%, 20%, 30% by weight of fine aggregate or cement.

Fine and Coarse Aggregates -

- ✚ River sand as fine aggregate.
- ✚ Crushed stone with a maximum size of 20 mm as coarse aggregate.
- ✚ Aggregates conforming to IS 383.

Water -

- ✚ Potable water used for mixing and curing.

Mix Design -

- ✚ Based on IS 10262: Concrete mix proportioning guidelines.
- ✚ Target grade: M20, M25, or M30 depending on the study scope.
- ✚ Control mix without any replacements.
- ✚ Several trial mixes with varying fly ash and limestone waste percentages.
- ✚ Water-Cement (w/c) ratio: Fixed or optimized for workability

Specimen Types and Sizes:

- ✚ **Compressive Strength:** Cubes (150 mm x 150 mm x 150 mm)
- ✚ **Split Tensile Strength:** Cylinders (150 mm diameter × 300 mm height)
- ✚ **Flexural Strength:** Prisms (100 mm × 100 mm × 500 mm)

Mechanical Testing:

- **Compressive Strength**
 - ✚ Conducted as per IS 516.
 - ✚ Testing ages: 7, 14, and 28 days.
 - ✚ Average of 3 specimens reported for each age and mix.
- **Split Tensile Strength**
 - ✚ As per IS 5816.
 - ✚ Cylinders tested after 28 days of curing.
- **Flexural Strength**
 - ✚ Prism specimens tested under third-point loading (IS 516).
 - ✚ 28-day flexural strength reported.

4. RESULT

Table 4.1 – Compressive Strength of NAC-0 Series (0% Lime Waste Stone) NAC usually stands for Normal Aggregate Concrete.

Mix Code	Fly Ash (%)	Strength @28 Days (MPa)
NAC-0-0	0	45.6
NAC-10-0	10	47.3
NAC-20-0	20	46.5
NAC-30-0	30	44.7

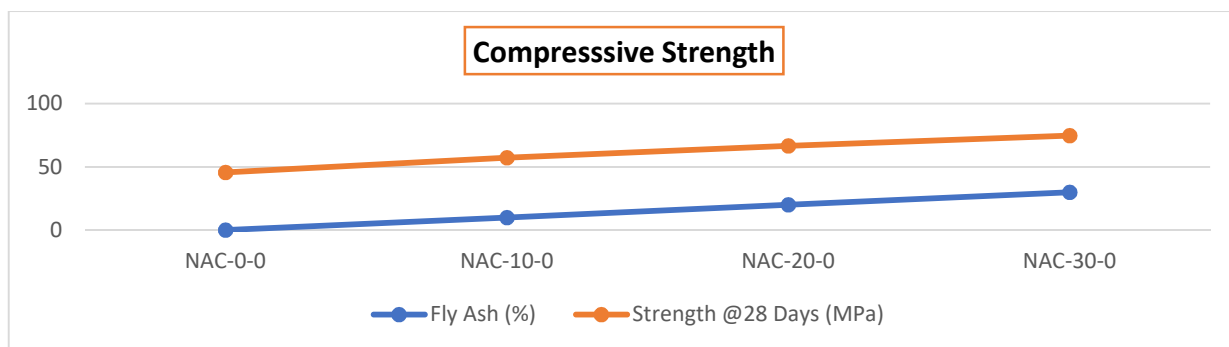


Table 42 – Compressive Strength for 25% Lime Waste Stone Replacement

Mix Code	Fly Ash (%)	7Days (MPa)	28Days (MPa)	60Days (MPa)	90Days (MPa)
NAC-0-25	0	25.07	42.86	45.70	48.16
NAC-10-25	10	22.80	41.14	43.30	52.58
NAC-20-25	20	21.50	35.44	37.50	42.50
NAC-30-25	30	18.33	30.92	32.48	35.35

Table 4.3 – Compressive Strength for 50% Lime Waste Stone Replacement

Mix Code	Fly Ash (%)	7Days (MPa)	28Days (MPa)	60Days (MPa)	90Days (MPa)
NAC-0-50	0	25.81	40.73	42.61	44.20
NAC-10-50	10	22.82	38.09	41.40	50.17
NAC-20-50	20	20.22	33.74	35.47	40.06
NAC-30-50	30	17.97	30.50	32.02	34.66

Table 4.4 – Compressive Strength for 75% Lime Waste Stone Replacement

Mix Code	Fly Ash (%)	7Days (MPa)	28Days (MPa)	60Days (MPa)	90Days (MPa)
NAC-0-75	0	23.50	37.50	39.62	41.27
NAC-10-75	10	21.13	35.24	37.81	46.60
NAC-20-75	20	19.00	30.66	32.46	38.27
NAC-30-75	30	16.90	27.38	28.90	32.00

Table 4.5 – Compressive Strength for 100% Lime Waste Stone Replacement

Mix Code	Fly Ash (%)	7Days (MPa)	28Days (MPa)	60Days (MPa)	90Days (MPa)
NAC-0-100	0	22.10	34.68	36.40	38.14
NAC-10-100	10	20.01	32.74	35.10	43.70
NAC-20-100	20	18.20	28.35	30.75	35.85
NAC-30-100	30	15.85	25.20	27.86	30.62

5.CONCLUSION

Based on the experimental investigation of sustainable concrete incorporating limestone waste and This study demonstrates that incorporating limestone waste and fly ash as partial replacements in concrete is both mechanically effective and environmentally beneficial. The experimental results indicate that optimal replacement levels up to 20% for both fly ash and limestone waste can improve or maintain the compressive, tensile, and flexural strengths compared to conventional concrete. Additionally, durability properties such as reduced water absorption and improved acid resistance were observed in modified mixes fly ash, from an environmental perspective, the use of fly ash and limestone waste significantly reduces the carbon footprint of concrete production by lowering cement usage and minimizing reliance on natural aggregates. The life-cycle assessment (LCA) confirmed notable reductions in CO₂ emissions and material extraction impacts, contributing to the sustainability goals of the construction industry. The following conclusions were drawn:

- The workability of concrete decreased slightly with increasing fly ash and limestone waste content due to their fineness and water absorption.
- Acceptable slump values were maintained up to 20% replacement levels.
- Concrete mixes with 10–20% replacement of cement/fine aggregate showed higher compressive strength than the control mix (NAC-0).
- The optimal performance was observed at 20% fly ash and 20% limestone waste, showing approximately 6–8% increase in 28-day compressive strength compared to conventional concrete.
- Split tensile and flexural strengths followed similar trends, with 20% replacement achieving the best balance of strength and durability.
- Strengths decreased beyond 30% replacement, indicating a limit to the effectiveness of waste substitution.
- The use of industrial waste materials like fly ash and limestone slurry contributes to environmental sustainability by reducing cement usage and promoting waste recycling.
- The approach helps lower CO₂ emissions, resource consumption, and cost in concrete production.
- Fly ash contributed to long-term strength due to its pozzolanic properties, while limestone waste enhanced particle packing and early strength.

Up to 20% replacement of cement and fine aggregate with fly ash and limestone waste can improve mechanical performance and support sustainable construction practices.

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