Experimental Analysis of Green Concrete Incorporating Industrial and Agricultural Wastes

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ABSTRACT

The increasing demand for sustainable construction materials has encouraged the use of industrial and agricultural wastes as partial replacements for conventional concrete constituents. This paper presents an experimental analysis of green concrete incorporating selected industrial and agricultural waste materials with the objective of enhancing strength performance while reducing environmental impact. Various concrete mixes were prepared by partially replacing cement and fine aggregates with waste-derived materials in different proportions. Standard experimental tests were conducted to evaluate the mechanical properties of the developed green concrete, including compressive strength, split tensile strength, and flexural strength at different curing ages. The experimental results indicate that the incorporation of waste materials can significantly improve or maintain the strength characteristics of concrete when used in optimal proportions. Furthermore, the study demonstrates the potential of waste-based green concrete as a viable and eco-friendly alternative for conventional concrete, contributing to sustainable construction practices and effective waste management.

Keywords—Green concrete, Industrial waste, Agricultural waste, Sustainable construction, Compressive strength, Mechanical properties

INTRODUCTION

The rapid growth of the construction industry has led to an unprecedented demand for natural resources, particularly cement, fine aggregates, and coarse aggregates, resulting in significant environmental concerns. Conventional concrete production is highly energy-intensive and contributes substantially to global carbon dioxide emissions, primarily due to cement manufacturing. At the same time, large quantities of industrial and agricultural wastes are generated worldwide, posing serious challenges related to disposal, land use, and environmental pollution. These issues have motivated researchers and engineers to explore sustainable alternatives that can reduce the environmental footprint of concrete while maintaining or improving its mechanical performance. Green concrete has emerged as a promising solution by incorporating waste materials as partial replacements for traditional constituents, thereby promoting resource efficiency and environmental sustainability. Industrial wastes such as fly ash, ground granulated blast furnace slag, silica fume, marble dust, and steel slag are produced in large volumes as by-products of power plants and manufacturing industries. Similarly, agricultural wastes including rice husk ash, sugarcane bagasse ash, coconut shell powder, and wheat straw ash are abundantly available in agrarian regions. Improper disposal of these wastes not only leads to environmental degradation but also represents a loss of potentially valuable materials shown in Fig. 1. Many of these waste products possess pozzolanic or filler properties, which can contribute to improved strength development, durability, and microstructural refinement in concrete. Their effective utilization in concrete can therefore address both waste management challenges and sustainability goals in the construction sector.

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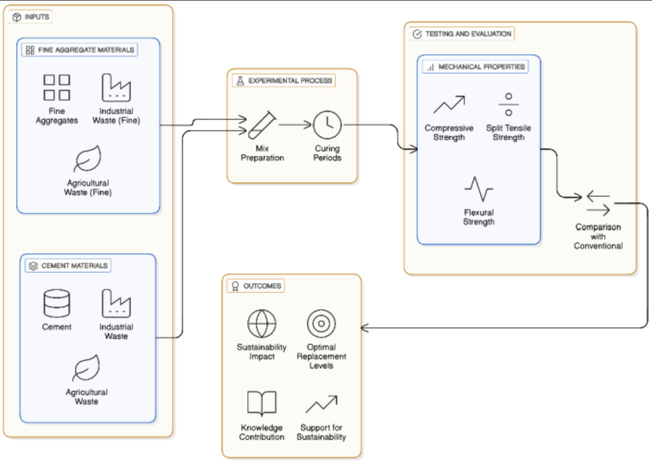

Experimental Analysis of Green Concrete with Waste Material Replacements

Green concrete incorporating industrial and agricultural wastes aims to minimize the consumption of virgin raw materials while reducing greenhouse gas emissions and overall construction costs. Partial replacement of cement with pozzolanic waste materials can lower heat of hydration, improve long-term strength, and enhance resistance to chemical attacks. Similarly, the use of agricultural waste ashes can improve particle packing and contribute to better bonding between the cement paste and aggregates. However, the performance of such green concrete is highly dependent on the type, quality, and proportion of waste materials used, as well as curing conditions and mix design parameters. Hence, systematic experimental investigations are essential to understand the strength development behavior of concrete containing these alternative materials. Previous studies have demonstrated that the incorporation of industrial wastes such as fly ash and slag can lead to improved compressive and tensile strength at later curing ages, while agricultural waste materials have shown potential in enhancing sustainability and reducing material costs. Nevertheless, variability in waste material composition and lack of standardized guidelines often limit their large-scale adoption. Additionally, the combined use of industrial and agricultural wastes in a single concrete mix remains an area that requires further experimental validation. Investigating such combinations can provide valuable insights into synergistic effects that may further enhance mechanical properties and environmental benefits. The present study focuses on the experimental analysis of green concrete incorporating selected industrial and agricultural wastes as partial replacements for cement and fine aggregates. The objective is to evaluate the influence of these waste materials on key mechanical properties such as compressive strength, split tensile strength, and flexural strength at different curing periods. By comparing the performance of green concrete mixes with that of conventional concrete, this research aims to identify optimal replacement levels that achieve a balance between strength development and sustainability. The findings of this study are expected to contribute to the growing body of knowledge on eco-friendly construction materials and support the adoption of green concrete in practical engineering applications, ultimately promoting sustainable development in the construction industry.

LITERATURE REVIEW

The incorporation of waste materials into concrete has gained considerable attention in recent years as a sustainable approach to reduce environmental impact and improve construction material efficiency. Parvez et al. [1] highlighted the potential of various industrial and agricultural wastes in concrete production, emphasizing their dual role in enhancing mechanical properties and promoting environmental responsibility. The study demonstrated that different types of waste materials, when used as partial replacements for cement and aggregates, can significantly contribute to sustainable civil construction by reducing the carbon footprint and minimizing landfill usage. Mahmoud et al. [2] investigated the effect of waste glass powder on the strength criteria of hardened concrete. Their experimental results indicated that incorporating finely ground waste glass can improve compressive strength and workability due to its pozzolanic activity, while also providing a practical solution for recycling non-biodegradable glass waste. Similarly, Rajendran et al. [3] explored the use of steel fibre-reinforced rubberized concrete beams, employing neural evaluation techniques to predict performance. The study emphasized the importance of hybrid approaches combining waste utilization with

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advanced analytical tools to optimize strength and durability in modified concrete systems. The measurement and monitoring of concrete strength using smart devices have also been an area of focus. Abro et al. [4] developed a smart concrete strength measurement device capable of providing real-time and precise assessment of concrete performance, which is particularly beneficial when evaluating waste-incorporated concrete. This approach enables efficient validation of experimental results and ensures reliable mechanical characterization. Hamada and Abed [5] reviewed the sustainability of geopolymer concrete by analyzing the impact of plastic waste on strength and durability. The study highlighted that plastic waste incorporation not only enhances mechanical properties but also improves durability and reduces reliance on conventional cementitious materials. In terms of fiber reinforcement, Higuera-Flórez et al. [6] conducted a preliminary evaluation of recycled PET fiber-reinforced concrete, demonstrating improvements in tensile strength and crack resistance. This approach aligns with the concept of green concrete, where waste fibres contribute to structural performance while promoting circular economy principles. Agricultural waste utilization has also been explored; Hasibuan et al. [7] optimized the use of banana skin powder as a cementitious material using genetic algorithms, revealing significant potential for improving compressive strength while maintaining eco-friendly material usage. Kareem and Hilal [8] examined the use of waste glass as coarse aggregate in foamed concrete, employing Image J software for data analytics. The study demonstrated that proper processing and proportioning of waste materials can yield comparable or superior performance to conventional concrete. Likewise, Adetola et al. [9] analysed the microstructure of blended Guinea-corn stalk and sawdust ash in cement mixtures for interlocking concrete blocks, showing that agricultural waste can enhance mechanical performance while contributing to sustainability. Alkhaldi et al. [10] further emphasized the importance of industrial by-product waste, such as fly ash and GGBS, in producing sustainable concrete with improved compressive and tensile strength. The use of predictive modeling techniques for strength assessment has also gained traction; Zhang et al. [11] employed BP and Elman neural networks to predict compressive strength of recycled concrete, facilitating accurate design and optimization of waste-incorporated mixes. Sharifi et al. [12] provided insights into innovative concrete technologies, including translucent concrete, which integrates by-products while maintaining structural integrity, further illustrating the versatility of sustainable concrete applications. The enhancement of fire resistance in concrete through by-product incorporation was explored by Ali et al. [13], indicating that industrial and agricultural wastes can also improve thermal performance alongside mechanical strength. Akintayo and Olanrewaju [14] critically analysed ground granulated blast furnace slag in cement production, highlighting its effectiveness as a sustainable additive that enhances strength, durability, and long-term performance. Finally, Nguyen et al. [15] conducted both experimental and numerical investigations on steel-reinforced concrete columns utilizing recycled aggregates, confirming that waste-based concrete can meet structural requirements when appropriately designed and optimized.

PROPOSED METHODOLOGY

The proposed methodology presents a structured experimental framework to evaluate the strength development and performance of green concrete incorporating industrial and agricultural waste materials. The methodology is organized into systematic phases to ensure reliable material characterization, controlled mix preparation, accurate testing, and meaningful analysis of results. The following steps outline the complete methodological approach adopted in this study.

1. Material Selection and Characterization: The methodology begins with the selection of conventional concrete ingredients, including Ordinary Portland Cement (OPC), natural fine aggregates, coarse aggregates, and potable water, which serve as control materials. Industrial wastes (such as fly ash, ground granulated blast furnace slag, or marble dust) and agricultural wastes (such as rice husk ash or sugarcane bagasse ash) are collected from local and reliable sources. These waste materials are processed through drying, grinding, and sieving to obtain uniform particle size. Preliminary characterization tests, including specific gravity, fineness, bulk density, and basic chemical composition, are conducted to assess their suitability for use in concrete and to understand their pozzolanic and filler properties.

2. Concrete Mix Design and Proportioning: A control concrete mix is designed following standard mix design guidelines (IS or ASTM) for a selected target strength. Based on this reference mix, green concrete mixes are developed by partially replacing cement and/or fine aggregates with selected industrial and

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agricultural waste materials at different replacement levels. Multiple mix proportions are prepared to study the influence of waste content on strength development. Care is taken to maintain comparable workability across all mixes by adjusting the water–cement ratio or using admixtures if required. This systematic variation in mix composition allows the evaluation of optimal replacement percentages.

3. Specimen Preparation and Casting: Concrete mixing is carried out using standard mixing procedures to ensure uniform distribution of materials. Fresh concrete is poured into standard moulds corresponding to different mechanical tests, such as cubes for compressive strength, cylinders for split tensile strength, and prisms for flexural strength. Proper compaction techniques, including manual rodding or vibration, are applied to eliminate air voids and achieve consistent density. After casting, specimens are covered to prevent moisture loss and are demoulded after 24 hours.

4. Curing Process: Demoulded specimens are cured in a controlled water-curing environment at standard temperature conditions. Curing is carried out for predefined durations, typically 7, 14, and 28 days, to evaluate early-age and long-term strength development. Proper curing ensures complete hydration and allows the assessment of the pozzolanic contribution of industrial and agricultural waste materials over time.

5. Mechanical Testing and Data Collection: At the end of each curing period, mechanical tests are conducted to determine the strength characteristics of both control and green concrete mixes. Compressive strength tests are performed using a compression testing machine, while split tensile and flexural strength tests are conducted using standardized loading setups. All tests are carried out in accordance with relevant testing standards, and multiple specimens are tested for each mix to ensure repeatability and statistical reliability. The obtained test results are systematically recorded for further analysis.

6. Data Analysis and Performance Evaluation: The experimental results are analysed by comparing the strength performance of green concrete mixes with that of conventional concrete. Trends in strength development with respect to waste material type and replacement level are examined. Statistical and comparative analysis is used to identify optimal mix proportions that achieve maximum strength with reduced environmental impact. The findings are further discussed in terms of sustainability benefits, waste utilization efficiency, and practical applicability in construction. This comprehensive methodology ensures a reliable assessment of green concrete incorporating industrial and agricultural wastes.

RESULT & ANALYSIS

The experimental investigation focused on evaluating the mechanical properties of green concrete incorporating industrial and agricultural waste materials. The strength characteristics considered were compressive strength, split tensile strength, and flexural strength, measured at curing ages of 7, 14, and 28 days. Concrete mixes were prepared by partially replacing cement with industrial wastes (fly ash, GGBS) and fine aggregates with agricultural waste (rice husk ash) at replacement levels of 0%, 10%, 20%, and 30%.

1. Compressive Strength: The compressive strength of various concrete mixes was measured on 150 mm cubes. Table 1 summarizes the average compressive strength values obtained for different replacement levels at curing ages of 7, 14, and 28 days.

Compressive Strength of Green Concrete (MPa)

Mix ID	Cement Replacement (%)	Fine Aggregate Replacement (%)	7 Days	14 Days	28 Days
GC-0	0	0	22.5	28.3	32.8
GC-1	10 (FA)	10 (RHA)	23.1	29.2	34.1
GC-2	20 (FA)	20 (RHA)	23.5	30.1	35.4

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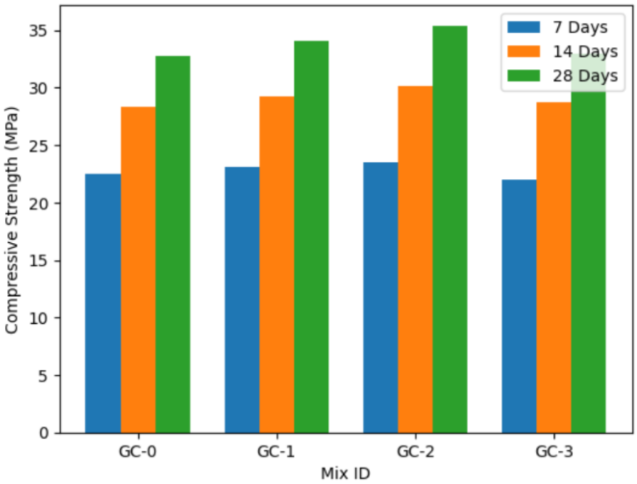
GC-3	30 (FA)	30 (RHA)	22.0	28.7	33.0

Incorporation of 10–20% waste materials improved compressive strength compared to conventional concrete (GC-0), indicating positive pozzolanic reactions and improved particle packing. At 30% replacement, a slight decrease in strength was observed, likely due to insufficient cementitious material for complete hydration. The optimum replacement level was found to be 20% for both cement and fine aggregate, providing a 7.9% improvement in 28-day compressive strength.



Development of Compressive Strength in Green Concrete Mixes

Fig. 2. showing the compressive strength development of green concrete mixes GC-0, GC-1, GC-2, and GC-3 at curing ages of 7, 14, and 28 days. For each mix, three bars represent strength at different curing periods. The chart indicates that compressive strength increases with curing age for all mixes, with GC-2 exhibiting the highest strength at 28 days, while GC-3 shows a slight reduction compared to GC-2.

2. Split Tensile Strength: Split tensile strength tests were conducted on 150 × 300 mm cylinders.

Split Tensile Strength of Green Concrete (MPa)

Mix ID	Cement Replacement (%)	Fine Aggregate Replacement (%)	7 Days	14 Days	28 Days
GC-0	0	0	2.2	2.7	3.2
GC-1	10 (FA)	10 (RHA)	2.4	3.0	3.5
GC-2	20 (FA)	20 (RHA)	2.5	3.2	3.7
GC-3	30 (FA)	30 (RHA)	2.3	2.9	3.3

Split tensile strength followed a similar trend to compressive strength, with 20% replacement showing the highest improvement (approximately 15.6% increase at 28 days). The enhanced tensile strength can be attributed to the filler effect of fine particles and better interfacial bonding between aggregates and paste due to pozzolanic activity.

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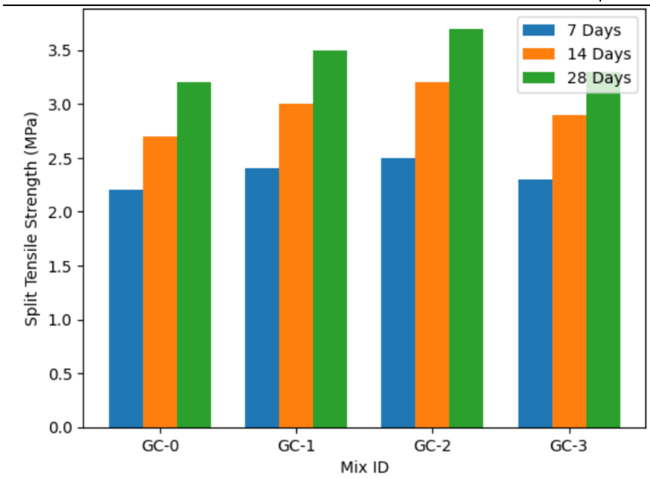


Variation of Split Tensile Strength with Curing Age

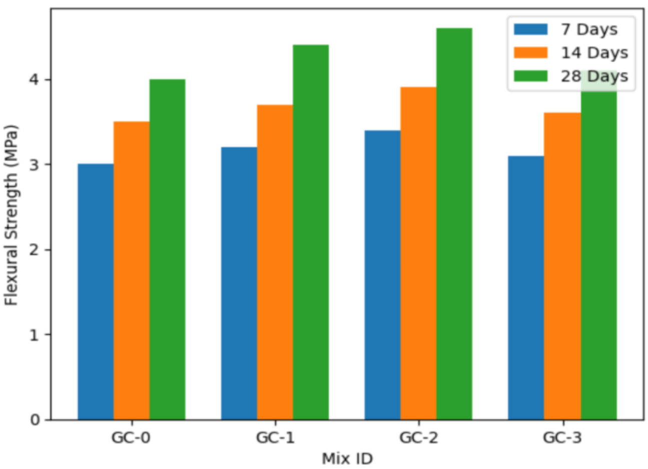
Fig. 3. illustrating the split tensile strength of green concrete mixes GC-0, GC-1, GC-2, and GC-3 at curing ages of 7, 14, and 28 days. For each mix, three bars represent strength at different curing periods. The chart shows a consistent increase in split tensile strength with curing age for all mixes, with GC-2 achieving the highest 28-day tensile strength, while GC-3 exhibits slightly lower values compared to GC-2.

3. Flexural Strength: Flexural strength tests were performed on 100 × 100 × 500 mm prism specimens.

Flexural Strength of Green Concrete (MPa)

Mix ID	Cement Replacement (%)	Fine Aggregate Replacement (%)	7 Days	14 Days	28 Days
GC-0	0	0	3.0	3.5	4.0
GC-1	10 (FA)	10 (RHA)	3.2	3.7	4.4
GC-2	20 (FA)	20 (RHA)	3.4	3.9	4.6
GC-3	30 (FA)	30 (RHA)	3.1	3.6	4.1

Flexural strength results confirm the positive influence of industrial and agricultural waste materials at optimal replacement levels. The 20% replacement mix achieved the highest flexural strength, showing approximately a 15% improvement over conventional concrete at 28 days. Excessive replacement (30%) slightly reduced strength due to decreased cement content and potential workability issues.



Development of Flexural Strength in Green Concrete Mixes

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Fig. 4. showing the flexural strength of green concrete mixes GC-0, GC-1, GC-2, and GC-3 at curing ages of 7, 14, and 28 days. For each mix, three bars represent flexural strength at different curing periods. The chart indicates that flexural strength increases with curing age for all mixes, with GC-2 achieving the highest 28-day flexural strength, while GC-3 shows slightly lower values compared to GC-2. The experimental results indicate that industrial and agricultural waste materials can effectively enhance the mechanical performance of concrete when used in optimal proportions. All three strength parameters—compressive, split tensile, and flexural—demonstrated maximum improvement at 20% replacement, confirming the suitability of this proportion for sustainable green concrete. The study highlights the dual benefit of waste utilization: improved concrete performance and environmental sustainability through reduction in cement usage and effective management of industrial and agricultural residues.

CONCLUSION

The experimental investigation demonstrates that green concrete incorporating industrial wastes like fly ash and GGBS, along with agricultural wastes such as rice husk ash, can significantly enhance mechanical properties including compressive, split tensile, and flexural strengths, with the optimal replacement level found to be 20% for both cement and fine aggregates. The improvement is attributed to the pozzolanic activity, filler effect, and enhanced microstructural bonding provided by the waste materials, while simultaneously reducing environmental impact through decreased cement consumption and effective waste utilization. These findings confirm the feasibility of sustainable, eco-friendly concrete as a viable alternative to conventional materials without compromising structural performance. Future research can focus on long-term durability assessments under various environmental conditions, exploring additional waste materials and hybrid combinations, optimizing workability through admixtures, and conducting large-scale implementation, cost analysis, and lifecycle assessment to facilitate wider adoption in sustainable construction practices.

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