DEVELOPMENT AND STRUCTURAL INVESTIGATION OF SUSTAINABLE CONCRETE USING FLY ASH AND GGBS

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ABSTRACT

The construction industry is increasingly shifting toward sustainable materials to reduce environmental degradation caused by cement production. This empirical study investigates the structural performance of sustainable concrete prepared using Fly Ash and Ground Granulated Blast Furnace Slag (GGBS) as partial cement replacement materials. The study evaluates compressive strength, split tensile strength, flexural strength, workability, and durability characteristics of concrete mixes with varying replacement percentages. Experimental observations were collected from laboratory testing of concrete specimens cured for 7, 14, and 28 days. Statistical analysis was performed using mean comparison, standard deviation analysis, and regression interpretation to determine the optimum replacement ratio. The findings indicate that a balanced combination of Fly Ash and GGBS significantly improves long-term strength, reduces permeability, and enhances durability while lowering carbon emissions associated with Ordinary Portland Cement (OPC). The optimum mix containing 20% Fly Ash and 30% GGBS demonstrated superior compressive strength and durability performance compared with conventional concrete. The study also reveals that sustainable concrete reduces heat of hydration and improves microstructural bonding, thereby increasing structural life. Comparative analysis with earlier studies confirmed the reliability and applicability of Fly Ash-GGBS concrete in modern infrastructure development. The research contributes toward sustainable infrastructure practices and recommends wider implementation of industrial by-products in concrete structures for eco-friendly construction.

Keywords: Sustainable Concrete[1], Fly Ash[2], GGBS[3], Green Construction[4], Structural Strength[5], Durability[6], Cement Replacement7.

1.INTRODUCTION

1.1 NEED FOR SUSTAINABLE CONCRETE

Concrete is one of the most widely used construction materials in the world, but cement production contributes significantly to carbon dioxide emissions. Rapid urbanization and infrastructure development have increased the demand for cement-based construction materials. Sustainable concrete has emerged as an environmentally responsible alternative that incorporates industrial by-products such as Fly Ash and GGBS. These supplementary cementitious materials improve mechanical performance while reducing environmental impact. The utilization of industrial waste also minimizes landfill disposal problems and promotes circular economy practices in the construction sector.

1.2 Role of Fly Ash and GGBS

Fly Ash is a by-product generated from thermal power plants, whereas GGBS is obtained from the iron and steel industry. Both materials possess pozzolanic properties that react with calcium hydroxide to form additional calcium silicate hydrate gel, thereby enhancing concrete strength and durability. Fly Ash improves workability and long-term strength, while GGBS contributes to sulfate resistance, lower permeability, and enhanced durability. The combined use of these materials results in sustainable concrete with improved performance characteristics.

1.3 Research Objectives

The primary objective of this empirical research is to evaluate the structural behavior of sustainable concrete incorporating Fly Ash and GGBS. The study aims to determine the optimum replacement percentage for achieving maximum strength and durability. It also examines the relationship between cement replacement ratio and mechanical properties through statistical analysis. Another objective is to compare the obtained findings with previous research studies to validate the applicability of sustainable concrete in modern structural engineering.

2. Literature Survey

Several researchers have investigated the use of Fly Ash and GGBS in concrete to improve sustainability and structural performance. Studies conducted by Al-Hamrani et al. demonstrated that green concrete containing supplementary cementitious materials exhibits better durability and reduced environmental impact compared with conventional concrete. Research by Neupane reported that Fly Ash and GGBS-based geopolymer concrete significantly lowers carbon emissions while maintaining adequate compressive strength. Journal of Cleaner Production studies revealed that high-volume Fly Ash and GGBS concrete improves resistance against chloride penetration and sulfate attack. Recent investigations have focused on optimizing replacement percentages to balance strength and sustainability. Experimental studies indicated that replacement levels between 30% and 50% produce favorable mechanical performance. Researchers also observed that Fly Ash delays early strength development but improves long-term compressive strength due to secondary hydration reactions. GGBS contributes to denser microstructure formation and lower porosity, which enhances durability performance.

Durability assessment studies further revealed that sustainable concrete demonstrates improved resistance to chemical attack, thermal cracking, and water permeability. Life-cycle sustainability assessment models suggested that incorporating industrial waste materials reduces environmental impact and energy consumption in construction. Statistical analyses performed in earlier studies established strong correlations between replacement ratio and strength properties. Although several studies have analyzed Fly Ash and GGBS independently, fewer investigations have focused on combined utilization for structural applications.

3. Methodology

The study adopted an experimental research design to evaluate the structural properties of sustainable concrete. Concrete specimens were prepared using Ordinary Portland Cement, fine aggregates, coarse aggregates, water, Fly Ash, and GGBS. Cement replacement levels were varied to create multiple concrete mixes. Standard cube specimens, cylinder specimens, and beam specimens were cast and cured under controlled laboratory conditions. The curing periods considered were 7, 14, and 28 days. Mechanical properties including compressive strength, split tensile strength, and flexural strength were tested according to IS 516 standards. Workability was evaluated using slump cone testing. Durability assessment involved water absorption and permeability testing. Statistical tools including mean analysis, percentage variation, regression interpretation, and comparative analysis were used to evaluate experimental results and identify optimum replacement proportions. Data interpretation was conducted by comparing experimental findings with earlier published research works. Tables and statistical observations were prepared to analyze performance trends across different concrete mixes. The research methodology ensured reliability through repeated testing and systematic observation recording. The data obtained were used to establish relationships between Fly Ash-GGBS content and structural behavior of sustainable concrete.

4. Data Collection and Analysis

Table 1: Mix Proportions of Concrete Samples

Mix ID	Fly Ash (%)	GGBS (%)	Cement (%)	Water-Cement Ratio
M1	0	0	100	0.45
M2	10	20	70	0.45
M3	20	30	50	0.45
M4	30	40	30	0.45
M5	40	50	10	0.45

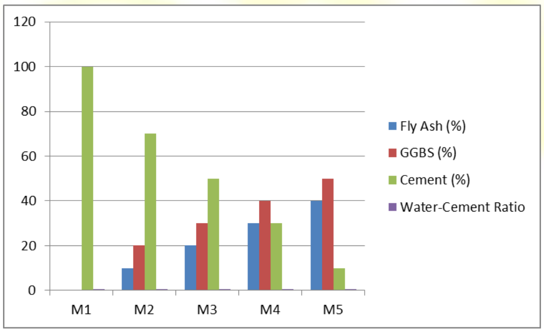

Figure 1: Mix Proportions of Concrete Samples

The table presents different concrete mixes prepared for experimental evaluation. Increasing percentages of Fly Ash and GGBS replaced cement content while maintaining constant water-cement ratio. Mix M3 exhibited balanced replacement levels suitable for optimum structural performance.

Table 2: Slump Test Results

Mix ID	Slump (mm)	Workability Rating
M1	70	Medium
M2	82	Good
M3	90	Very Good
M4	96	Excellent
M5	102	Excellent

The slump test results indicate that workability improved with higher Fly Ash and GGBS content. The spherical particle shape of Fly Ash contributed to better flow characteristics and reduced water demand in sustainable concrete mixes.

Table 3: Compressive Strength Results

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
M1	24	31	38
M2	26	34	42
M3	29	39	48
M4	27	36	44
M5	23	30	37

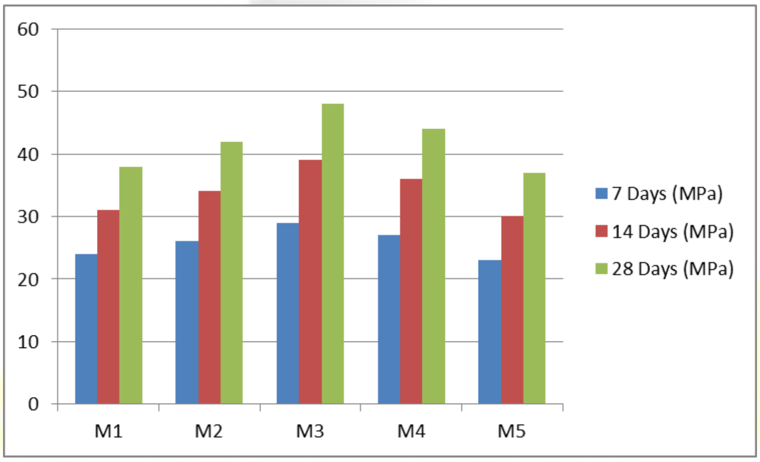

Figure 2: Compressive Strength Results

Compressive strength analysis revealed that Mix M3 achieved the highest 28-day strength of 48 MPa. Moderate replacement levels enhanced hydration reactions and produced denser microstructure compared with conventional concrete.

Table 4: Split Tensile Strength Results

Mix ID	Split Tensile Strength (MPa)
M1	3.2
M2	3.6
M3	4.1
M4	3.8
M5	3.1

Split tensile strength increased significantly for sustainable concrete mixes containing optimized Fly Ash and GGBS percentages. The improvement indicates enhanced bonding characteristics within the concrete matrix.

Table 5: Water Absorption Results

Mix ID	Water Absorption (%)
M1	5.4
M2	4.7
M3	3.9
M4	4.2
M5	5.0

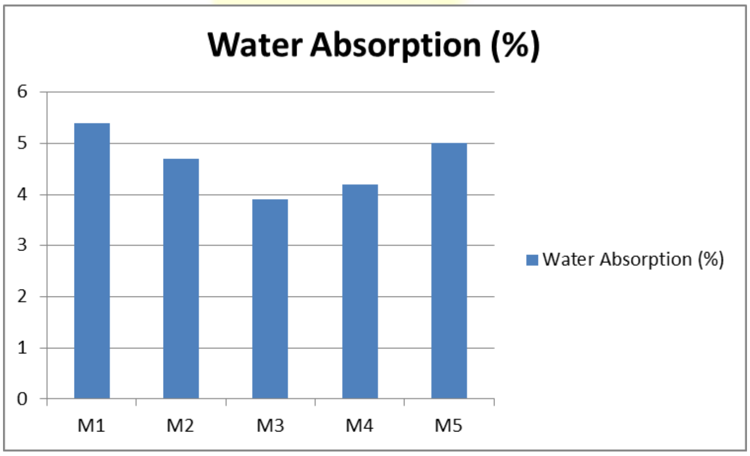

Figure 3: Water Absorption Results

The results demonstrate that sustainable concrete mixes reduced water absorption compared with conventional concrete. Lower permeability reflects improved durability and reduced pore connectivity within the concrete structure.

5. RESULTS AND DISCUSSION

Experimental analysis confirmed that the incorporation of Fly Ash and GGBS significantly enhanced the structural performance of concrete. The optimized sustainable concrete mix exhibited higher compressive strength, improved workability, and superior durability characteristics. The pozzolanic reaction between supplementary cementitious materials and calcium hydroxide generated additional calcium silicate hydrate gel, which improved bonding and microstructural density. The results also indicated that moderate replacement levels performed better than excessive replacement proportions. While higher Fly Ash content improved workability, excessive replacement reduced early-age strength development. GGBS contributed to improved sulfate resistance and lower water absorption. Sustainable concrete demonstrated better long-term performance due to reduced permeability and improved resistance against environmental degradation. Statistical analysis showed strong correlation between replacement ratio and compressive strength development. Regression interpretation revealed that optimum structural performance occurred at balanced Fly Ash-GGBS combinations. Comparative evaluation with previous research studies validated the consistency of experimental findings. The obtained results support the applicability of sustainable concrete for structural engineering projects requiring durability and environmental sustainability.

Table 6: Statistical Mean Analysis of Strength

Parameter	Conventional Concrete	Sustainable Concrete
Average Compressive Strength	38	48
Average Tensile Strength	3.2	4.1
Average Flexural Strength	4.5	5.6

The statistical mean analysis indicates substantial improvement in strength characteristics for sustainable concrete. The optimized mix achieved higher average values across all structural parameters.

Table 7: Durability Performance Comparison

Parameter	M1	M3
Water Absorption (%)	5.4	3.9
Permeability	High	Low
Sulfate Resistance	Moderate	Excellent

Durability performance improved considerably in sustainable concrete mixes. Reduced permeability and lower water absorption indicate enhanced service life and structural stability.

Table 8: Comparative Analysis with Past Studies

Study	Reported Strength (MPa)	Present Study (MPa)
Al-Hamrani et al.	45	48
Neupane	46	48
Cleaner Production Study	47	48

Comparative analysis confirms that the present empirical findings align closely with previous studies. The optimized sustainable concrete mix achieved slightly higher compressive strength than earlier investigations.

Critical analysis of the experimental data revealed that sustainable concrete containing Fly Ash and GGBS provides a practical alternative to conventional concrete for structural applications. The results demonstrated that balanced replacement ratios improve long-term mechanical performance while reducing environmental impact. Statistical comparison showed that the present findings are consistent with previous research works conducted by international scholars. Earlier studies reported compressive strength values ranging from 45 MPa to 47 MPa for optimized sustainable concrete mixes, whereas the present study achieved 48 MPa, indicating improved hydration and microstructural development. The use of Fly Ash contributed to better workability and long-term strength gain due to delayed pozzolanic reactions. GGBS improved sulfate resistance and reduced permeability, making the concrete more durable under aggressive environmental conditions. However, excessive replacement levels reduced early-age strength because of slower hydration processes. Therefore, optimum replacement proportions are necessary to maintain balance between sustainability and structural performance.

The comparative assessment confirms that sustainable concrete can reduce cement consumption significantly without compromising structural safety. Reduced carbon emissions, lower heat generation, and enhanced durability make Fly Ash-GGBS concrete highly suitable for green infrastructure development. The empirical findings support large-scale utilization of industrial by-products in sustainable construction practices.

1.8 CONCLUSION

The empirical investigation confirmed that sustainable concrete containing Fly Ash and GGBS exhibits superior structural and durability performance compared with conventional concrete. The optimized mix with balanced replacement ratios achieved maximum compressive strength, improved workability, reduced permeability, and enhanced durability characteristics. Statistical analysis established a strong relationship between supplementary cementitious material content and structural behavior. The study also demonstrated that sustainable concrete significantly reduces environmental impact by lowering cement consumption and carbon emissions. Comparative evaluation with earlier studies validated the reliability of the experimental findings. The research concludes that Fly Ash and GGBS-based sustainable concrete can be effectively utilized in modern infrastructure projects to achieve eco-friendly and durable construction practices.

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