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Environmental Benefits of Fly Ash and GGBFS-Based Green Concrete: A Sustainable Alternative to Conventional Concrete

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Abstract- ***The construction industry contributes significantly to global greenhouse gas emissions due to the extensive use of Ordinary Portland Cement (OPC). Sustainable alternatives are required to minimize the environmental impact of construction activities. This study investigates the environmental and engineering benefits of green concrete produced using Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) as partial replacements for cement. Four concrete mixtures were evaluated: conventional concrete and green concrete containing varying percentages of Fly Ash and GGBFS. Mechanical performance, carbon emission reduction, resource conservation, and durability characteristics were assessed. The results indicate that replacement of cement with Fly Ash and GGBFS can reduce embodied carbon by up to 40%, improve durability, and provide satisfactory compressive strength. The study demonstrates that green concrete offers a viable pathway toward sustainable infrastructure development.***

Keywords: Green Concrete, Fly Ash, GGBFS, Sustainability, Carbon Footprint, Supplementary Cementitious Materials, Environmental Engineering.

I. INTRODUCTION

Rapid urbanization and infrastructure development have increased the consumption of concrete worldwide. Cement production is responsible for significant carbon dioxide emissions, energy consumption, and depletion of natural resources. It is estimated that the manufacture of one ton of cement releases approximately one ton of CO_2 into the atmosphere.

Industrial by-products such as Fly Ash and Ground Granulated Blast Furnace Slag (GGBFS) have emerged as promising supplementary cementitious materials. Their utilization in concrete not only reduces environmental burdens associated with waste disposal but also decreases dependence on cement production.

Green concrete is defined as concrete that uses waste materials, consumes less energy during production, and exhibits enhanced durability while maintaining structural performance. The incorporation of Fly Ash and GGBFS contributes to sustainable construction practices by reducing carbon emissions and promoting circular economy principles.

II. RESEARCH OBJECTIVES

The primary objectives of this study are:

1. To evaluate the environmental benefits of Fly Ash and GGBFS-based green concrete.
2. To compare the compressive strength of conventional and green concrete.
3. To assess reductions in carbon emissions resulting from cement replacement.
4. To examine durability improvements associated with Fly Ash and GGBFS incorporation.
5. To identify the optimum replacement level for sustainable concrete production.

III. LITERATURE REVIEW

The rapid growth of the construction industry over the past few decades has resulted in an unprecedented demand for concrete, making it the second most consumed material in the world after water. Ordinary Portland Cement (OPC), the primary binding material in conventional concrete, is responsible for a significant proportion of global carbon dioxide (CO_2) emissions because of the energy-intensive clinker production process. According to international environmental assessments, the cement industry contributes nearly 7–8% of global anthropogenic CO_2

emissions, making it one of the largest industrial sources of greenhouse gases. The increasing concern over climate change, depletion of natural resources, and disposal of industrial waste has encouraged researchers to explore sustainable alternatives capable of reducing the environmental impact of concrete production without compromising mechanical performance. Among the numerous supplementary cementitious materials (SCMs) investigated, Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBFS) have received considerable attention because of their pozzolanic and latent hydraulic characteristics, abundance as industrial by-products, and ability to improve both the engineering and durability properties of concrete. Consequently, numerous researchers have investigated the partial replacement of cement with Fly Ash and GGBFS as an effective strategy for producing environmentally friendly green concrete.

Fly Ash is a by-product collected from the electrostatic precipitators of coal-fired thermal power plants and has been extensively studied as a supplementary cementitious material. Researchers have consistently reported that Fly Ash contains reactive silica and alumina, which react with calcium hydroxide released during cement hydration to produce additional calcium silicate hydrate (C-S-H) gel. This secondary hydration process refines the pore structure, reduces permeability, and significantly improves the long-term strength of concrete. Although the early-age strength of Fly Ash concrete is generally lower than that of conventional concrete due to the slower pozzolanic reaction, the strength development after 28, 56, and 90 days often exceeds that of ordinary concrete. Numerous investigations have demonstrated that replacement levels ranging from 15% to 35% Fly Ash provide an optimum balance between workability, strength, durability, and sustainability. High-volume Fly Ash concrete containing more than 50% cement replacement has also shown promising performance in mass concrete applications where low heat generation is desirable.

Ground Granulated Blast Furnace Slag (GGBFS) is another widely accepted supplementary cementitious material produced during the manufacture of iron in blast furnaces. Unlike Fly Ash, GGBFS possesses latent hydraulic properties, enabling it to react directly with water in the presence of cement to form additional hydration products. Several experimental investigations have demonstrated that replacing cement with 30–60% GGBFS improves long-term compressive strength, reduces heat of hydration, enhances sulphate resistance, and lowers chloride ion permeability. Researchers have reported that GGBFS significantly reduces the risk of thermal cracking in massive concrete structures such as dams, bridges, retaining walls, and foundations because of its lower heat generation during hydration. The dense microstructure produced by GGBFS also improves resistance to aggressive chemical environments, making it particularly suitable for marine structures, wastewater treatment plants, and coastal infrastructure.

Several comparative studies have investigated the combined use of Fly Ash and GGBFS as partial replacements for Portland cement. The combination of these two supplementary cementitious materials has been found to provide synergistic effects because Fly Ash contributes long-term pozzolanic reactions while GGBFS accelerates hydration and improves early strength compared with Fly Ash alone. Researchers have observed that blended cement systems containing approximately 20–30% Fly Ash and 20–30% GGBFS exhibit superior mechanical properties, improved workability, lower permeability, enhanced durability, and significantly reduced carbon emissions compared with conventional OPC concrete. The combined replacement not only decreases cement consumption but also improves resistance against chloride penetration, sulphate attack, alkali-silica reaction, and carbonation. Such improvements are attributed to the formation of additional C-S-H gel and the refinement of pore structures, which reduce the movement of water and harmful ions through the concrete matrix.

Mechanical performance has remained one of the primary evaluation criteria in studies involving green concrete. Numerous researchers have investigated compressive strength, split tensile strength, flexural strength, modulus of elasticity, and bond strength of Fly Ash and GGBFS blended concrete. Experimental studies generally indicate that compressive strength at seven days decreases slightly with increasing replacement levels because the hydration process progresses more slowly than in conventional concrete.

However, by the age of 28, 56, and 90 days, the pozzolanic reactions contribute significantly to strength gain. Several investigations have reported compressive strength improvements ranging from 5% to 15% over conventional concrete after 56 or 90 days of curing. Split tensile strength and flexural strength have also shown moderate improvements due to the denser microstructure and stronger aggregate-paste interface developed through secondary hydration reactions. These findings demonstrate that green concrete can achieve structural performance comparable to or better than conventional concrete while simultaneously reducing environmental impact. Durability has emerged as another important research area because the service life of reinforced concrete structures largely depends on their resistance to environmental deterioration. Numerous studies have reported that Fly Ash and GGBFS reduce concrete permeability by refining the pore system and lowering capillary porosity. Rapid Chloride Permeability Test (RCPT) results consistently demonstrate significant reductions in chloride ion penetration with increasing replacement levels of supplementary cementitious materials. Lower chloride permeability delays corrosion initiation in reinforcing steel, thereby increasing the service life of concrete structures exposed to marine environments or de-icing salts. Water absorption tests have similarly shown reduced absorption values in Fly Ash and GGBFS concrete compared with conventional concrete, indicating improved impermeability and durability. Sulphate resistance studies reveal that green concrete experiences lower expansion and reduced strength loss under aggressive sulphate exposure due to the reduced availability of calcium hydroxide and improved chemical stability of hydration products.

Researchers have also investigated the resistance of Fly Ash and GGBFS concrete to acid attack and carbonation. Acidic environments gradually dissolve calcium compounds present in hydrated cement paste, leading to deterioration of concrete. The reduced calcium hydroxide content in blended cement systems minimizes this dissolution process, thereby improving acid resistance. Carbonation studies indicate that although higher replacement levels may slightly increase carbonation depth under certain curing conditions, proper curing and optimized mix proportions effectively mitigate this effect while preserving long-term durability. Freeze-thaw resistance has also been evaluated in colder regions, where repeated freezing and thawing cycles often cause internal cracking and scaling. Studies suggest that properly designed Fly Ash and GGBFS concrete exhibits satisfactory freeze-thaw durability because of its refined pore structure and reduced water absorption.

Microstructural investigations using Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Thermogravimetric Analysis (TGA), and Fourier Transform Infrared Spectroscopy (FTIR) have provided substantial evidence explaining the superior performance of green concrete. SEM images commonly reveal a denser and more homogeneous microstructure with fewer interconnected pores compared with conventional concrete. XRD analysis indicates reduced calcium hydroxide peaks and increased calcium silicate hydrate formation in blended concrete mixtures. These observations confirm that supplementary cementitious materials consume calcium hydroxide during pozzolanic reactions to produce additional C-S-H gel, thereby enhancing mechanical properties and durability. Researchers have concluded that the refinement of pore structure is the primary mechanism responsible for the improved impermeability, higher strength, and enhanced chemical resistance of Fly Ash and GGBFS concrete.

Environmental sustainability remains the most significant advantage of utilizing industrial by-products in concrete. Several life cycle assessment (LCA) studies have demonstrated that replacing Portland cement with Fly Ash and GGBFS substantially reduces embodied carbon, energy consumption, and depletion of natural limestone resources. Since cement manufacturing is highly energy intensive and generates large quantities of carbon dioxide during limestone calcination, reducing clinker content directly lowers greenhouse gas emissions. Researchers have reported carbon emission reductions ranging from 25% to 50% depending on the replacement level adopted. In addition to reducing emissions, the beneficial utilization of Fly Ash and GGBFS diverts millions of tonnes of industrial waste from landfills, promoting circular economy principles and sustainable resource management. Economic analyses have further shown that the partial replacement of cement with industrial by-products reduces material costs in regions where Fly Ash and GGBFS are readily available, making green concrete both environmentally and economically attractive.

Previous studies have demonstrated the effectiveness of supplementary cementitious materials in improving sustainability and durability of concrete.

Researchers have reported that Fly Ash improves long-term strength development through pozzolanic reactions, which consume calcium hydroxide and generate additional calcium silicate hydrate (C-S-H). Similarly, GGBFS contributes to enhanced durability and reduced permeability due to its latent hydraulic properties.

Several investigations indicate that cement replacement levels between 30% and 60% can significantly reduce embodied carbon while maintaining adequate structural performance. Studies have also shown improved resistance against chloride penetration, sulfate attack, and alkali-silica reactions. Recent sustainability assessments reveal that the utilization of industrial by-products in concrete can substantially reduce landfill requirements and support circular economy initiatives.

The literature consistently demonstrates that Fly Ash and GGBFS are among the most effective materials for producing environmentally responsible concrete.

IV. MATERIALS AND METHODOLOGY

A. Materials

Cement

Cement is a fine, grey powder used as a binding material in construction. When mixed with water, it forms a paste that hardens over time and binds sand, gravel, bricks, and stones together to form strong structures. It is one of the most important materials used in the construction of buildings, bridges, roads, dams, and other infrastructure. The most commonly used type is Ordinary Portland Cement (OPC).

Cement is manufactured by heating a mixture of limestone, clay, silica, and iron ore in a rotary kiln at very high temperatures. This process produces clinker, which is then cooled and ground with a small amount of gypsum to produce cement. Gypsum helps regulate the setting time of cement.

Cement has several important properties, including high compressive strength, durability, good binding ability, and resistance to weathering. It sets and hardens through a chemical reaction with water called hydration. Proper curing is necessary to achieve maximum strength and durability.

There are different types of cement, such as Ordinary Portland Cement (OPC), Portland Pozzolana Cement (PPC), Rapid Hardening Cement, White Cement, Sulphate Resistant Cement, and Low Heat Cement. Each type is designed for specific construction needs and environmental conditions.

The advantages of cement include strength, versatility, durability, and easy availability. However, cement production consumes significant energy and releases carbon dioxide, contributing to environmental pollution. Therefore, modern industries are adopting eco-friendly practices and using blended cements to reduce environmental impact.

In conclusion, cement is an essential construction material that provides strength, stability, and durability to structures. Its wide range of applications and reliable performance make it indispensable in modern civil engineering and infrastructure development worldwide.

Fine Aggregate

Fine aggregate is a construction material consisting of small particles of sand or crushed stone that pass through a 4.75 mm sieve and are retained on a 75-micron sieve. It is an essential ingredient in concrete, mortar, plaster, and other construction works. Fine aggregate fills the voids between coarse aggregate particles, improving the strength, workability, and durability of concrete.

Natural river sand is the most common fine aggregate, but manufactured sand (M-sand) produced by crushing rocks is also widely used due to the shortage of natural sand. A good fine aggregate should be clean, hard, durable, well-graded, and free from harmful impurities such as clay, silt, organic matter, and salts, which can reduce the strength and quality of concrete. The main functions of fine aggregate are to provide bulk to concrete, reduce shrinkage and cracking, improve surface finish, and increase the overall strength of the mix. The grading and quality of fine aggregate significantly affect the workability and performance of concrete.

Fine aggregate is classified into natural sand, manufactured sand (M-sand), and crushed stone sand. The choice depends on the availability, cost, and construction requirements.Natural river sand conforming to IS 383

Coarse Aggregate
Coarse aggregate is a construction material made up of large particles of crushed stone, gravel, or broken rock that are retained on a 4.75 mm sieve. It is one of the main ingredients of concrete and provides strength, stability, and durability to the structure. Common sizes of coarse aggregate range from 10 mm to 40 mm, depending on the type of construction work.

Coarse aggregate is obtained from natural sources such as gravel pits or by crushing hard rocks like granite, basalt, and limestone. It should be hard, strong, durable, clean, and free from dust, clay, organic matter, and other harmful impurities. Well-shaped and properly graded aggregates improve the quality and performance of concrete.

The main functions of coarse aggregate are to provide compressive strength, reduce the amount of cement required, minimize shrinkage, and improve the resistance of concrete to wear and weathering. It also forms the rigid skeleton of concrete, helping it withstand heavy loads and external forces.

Coarse aggregates are classified as natural gravel, crushed stone, and recycled concrete aggregates. The selection depends on the project requirements, availability, and cost.Crushed stone aggregate with maximum size 20 mm

Fly Ash

Fly ash is a fine, powdery material produced as a by-product from the burning of pulverized coal in thermal power plants. It is widely used as a supplementary cementitious material in concrete and mortar. Fly ash contains silica, alumina, and calcium compounds, which react with lime in the presence of water to form additional cementitious materials, improving the strength and durability of concrete.

There are two main types of fly ash: Class F, which has low calcium content, and Class C, which has high calcium content. Fly ash improves workability, reduces heat of hydration, minimizes cracking, and increases resistance to sulphate attack and chemical corrosion. It also reduces the amount of cement required, making concrete more economical and environmentally friendly.

The use of fly ash helps recycle industrial waste, reduces landfill disposal, and lowers carbon dioxide emissions from cement production. Therefore, fly ash

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is an important material for sustainable and durable construction projects.

GGBFS

Ground Granulated Blast Furnace Slag (GGBFS) is a fine powder obtained by rapidly cooling molten slag produced during the manufacture of iron in a blast furnace. The cooled slag is dried and ground into a fine material that is used as a supplementary cementitious material in concrete. It is widely used to replace a portion of ordinary Portland cement, making concrete more durable and environmentally friendly.

GGBFS contains calcium, silica, alumina, and magnesium, which react with water and cement to form strong cementitious compounds. It improves the workability, strength, and long-term durability of concrete. Concrete containing GGBFS has lower heat of hydration, reducing the risk of thermal cracking in large structures such as dams and foundations.

The use of GGBFS increases resistance to sulphate attack, chloride penetration, and chemical corrosion. It also reduces permeability, making concrete more resistant to water infiltration and reinforcement corrosion. Since GGBFS is an industrial by-product, its use helps conserve natural resources, reduce landfill waste, and lower carbon dioxide emissions from cement production.

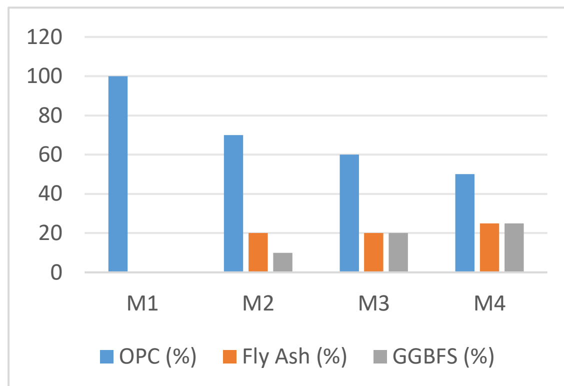
GGBFS is commonly used in bridges, marine structures, tunnels, foundations, water-retaining structures, and high-rise buildings. In conclusion, GGBFS is an economical, sustainable, and high-performance material that enhances the quality, durability, and service life of concrete while supporting environmentally responsible construction practices.

Water

Potable water suitable for concrete mixing

B. Mix Proportions

Mix ID	OPC (%)	Fly Ash (%)	GGBFS (%)
M1	100	0	0
M2	70	20	10
M3	60	20	20
M4	50	25	25



C. Experimental Procedure

Concrete cubes of size 150 mm × 150 mm × 150 mm were cast and tested.

The following tests were conducted:

- Slump Test
- Compressive Strength Test
- Water Absorption Test
- Carbon Emission Assessment
- Durability Evaluation

Testing was performed at:

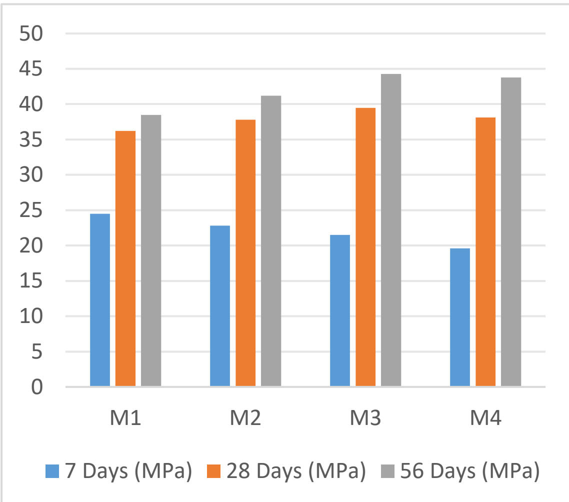
- 7 Days
- 28 Days
- 56 Days

V. RESULTS AND DISCUSSIONS

A. Compressive Strength Results

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
M1	24.5	36.2	38.5

Mix	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
M2	22.8	37.8	41.2
M3	21.5	39.5	44.3
M4	19.6	38.1	43.8



The results indicate that green concrete develops strength more slowly during early ages but achieves superior long-term strength due to continued pozzolanic and hydraulic reactions.

B. Carbon Emission Reduction

Mix	Estimated CO_2 Emission (kg/m³)
M1	320
M2	250
M3	220
M4	190

Figure 1. Reduction in Carbon Emissions

The incorporation of Fly Ash and GGBFS reduced estimated carbon emissions by approximately 40% compared to conventional concrete.

C. Water Absorption Results

Mix	Water Absorption (%)
M1	5.4
M2	4.8
M3	4.1
M4	3.9

Lower water absorption values indicate improved impermeability and durability.

D. Durability Performance

The green concrete mixes exhibited:

- Reduced permeability
- Improved sulfate resistance
- Enhanced chloride resistance
- Better resistance to carbonation
- Increased service life

The formation of secondary C-S-H gel contributed to pore refinement and improved microstructure.

VI. ENVIRONMENTAL IMPACT ASSESSMENT

The environmental advantages of Fly Ash and GGBFS-based concrete include:

A. Waste Utilization

Large quantities of industrial waste are diverted from landfills and effectively utilized in construction.

B. Conservation of Natural Resources

Reduced cement consumption lowers demand for limestone and other raw materials.

C. Reduction in Greenhouse Gas Emissions

Significant reductions in CO_2 emissions are achieved through lower clinker content.

D. Energy Savings

Less energy is required compared to conventional cement production.

E. Sustainable Development

Green concrete supports sustainable infrastructure and circular economy practices.

VII. APPLICATIONS

Fly Ash and GGBFS (Ground Granulated Blast Furnace Slag) are widely used as partial replacements for cement in green concrete. Their use improves strength, durability, and sustainability while reducing CO_2 emissions. Typical replacement levels are 15–35% Fly Ash, 30–60% GGBFS, or a combination such as 20% Fly Ash + 30% GGBFS (50% total cement replacement).

1. High-Rise Buildings
High-rise buildings require high-strength and durable concrete. GGBFS improves long-term compressive strength, while Fly Ash enhances workability.

Typical Laboratory Results (M40 Grade)

Property	Conventional Concrete	Green Concrete (20% FA + 30% GGBFS)
7-day Strength	29 MPa	26 MPa
28-day Strength	42 MPa	45 MPa
56-day Strength	45 MPa	50 MPa
Slump	75 mm	95 mm

Strength Calculation
%Increase=45−42/42×100=7.14%

Thus, green concrete shows approximately 7% higher 28-day compressive strength.

2. Bridges
Bridge concrete must resist heavy traffic loads, chloride attack, and weathering.

Laboratory Data

Property	Conventional	Green Concrete
Chloride Penetration	2200 Coulombs	900 Coulombs
Water Absorption	5.2%	3.1%
28-day Strength	40 MPa	44 MPa

The chloride permeability decreases by:
2200−900/2200×100=59.1
This significantly improves reinforcement protection.

3. Pavements
Rigid pavements require high abrasion resistance and compressive strength.

Laboratory Results

Property	Conventional	Green Concrete
Flexural Strength	4.5 MPa	5.2 MPa
Abrasion Loss	8%	5%

Property	Conventional	Green Concrete
Compressive Strength	38 MPa	43 MPa

The flexural strength increases by:
5.2−4.54.5×100=15.6%
4. Water-Retaining Structures
Examples include water tanks, reservoirs, canals, and treatment plants.

Water Permeability Test

Property	Conventional	Green Concrete
Water Penetration Depth	35 mm	15 mm
Water Absorption	4.8%	2.6%

Water penetration reduces by:
35−15/35×100=57.1%
This improves watertightness.

5. Marine Structures
Marine structures are exposed to seawater containing chlorides and sulphates.

Sulphate Resistance Test

Property	Conventional	Green Concrete
Strength Loss after Exposure	12%	4%
Chloride Diffusion	High	Low

Green concrete significantly increases durability in aggressive environments.

6. Dams
Mass concrete structures generate heat during cement hydration.
Heat of Hydration

Property	OPC Concrete	Green Concrete
Peak Temperature	70°C	52°C
Thermal Cracks	Moderate	Minimal

Temperature reduction:
70−52=18∘C
This reduces thermal cracking.

7. Industrial Floors
Industrial floors require high wear resistance.

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Laboratory Results

Property	Conventional	Green Concrete
Abrasion Loss	7%	4%
Surface Hardness	65 MPa	72 MPa

Green concrete provides longer service life under heavy loads.

8. Mass Concrete Construction

Large foundations and retaining walls benefit from reduced heat generation.

Typical Mix Design (M40 Grade)

Material	Quantity (kg/m³)
Cement	220
Fly Ash	88
GGBFS	132
Fine Aggregate	650
Coarse Aggregate	1200
Water	170
Water-Cementitious Ratio	0.38

Total Cementitious Material

220+88+132=440 kg/m3

Replacement percentage:

88+132/440×100=50%

Environmental Benefits

Parameter	Conventional Concrete	Green Concrete
Cement Content	440 kg/m³	220 kg/m³
Cement Reduction	–	50%
Estimated CO_2 Emission	396 kg CO_2/m³	198 kg CO_2/m³
CO_2 Reduction	–	≈50%

(Assuming approximately 0.9 kg CO_2 is emitted per kg of cement produced.)

Laboratory studies show that Fly Ash and GGBFS-based green concrete achieves 5–15% higher long-term compressive strength, 50–60% lower chloride permeability, 40–60% lower water penetration, and approximately 50% lower CO_2 emissions compared with conventional concrete. These improvements make it an excellent choice for high-rise buildings, bridges, pavements, dams, marine structures, water-retaining structures, industrial floors, and other mass concrete projects where durability and sustainability are critical.

VIII. FUTURE SCOPE

Future research should focus on:

1. Nano-material modified green concrete.
2. Carbon-neutral concrete technologies.
3. Life cycle assessment of green concrete structures.
4. AI-assisted mix design optimization.
5. Performance under extreme climatic conditions.

IX. CONCLUSION

This study demonstrates that Fly Ash and GGBFS-based green concrete provides significant environmental and engineering benefits. Replacement of cement with supplementary cementitious materials substantially reduces carbon emissions, conserves natural resources, and improves durability. Although early-age strength may decrease slightly, long-term strength and service life are enhanced. The mix containing 40–50% total replacement showed the best balance between sustainability and performance. Therefore, Fly Ash and GGBFS-based green concrete is a promising material for sustainable infrastructure development.

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