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PERFORMANCE ASSESSMENT OF HIGH-VOLUME GGBS CONCRETE FOR LONG-TERM STRUCTURAL DURABILITY AND SUSTAINABILITY

Anil Kumar Yadav*[1], Dr. Maroof Khan[2]

[1]M.Tech. Scholar, [2]Associate professor

School of Civil Engineering, Faculty of Engineering and Technology Madhyanchal Professional University Bhopal, M.P.

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***Corresponding Author: Anil Kumar Yadav**

M. Tech. Scholar, School of Civil Engineering, Faculty of Engineering and Technology Madhyanchal Professional University Bhopal, M.P.

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ABSTRACT

This study investigates the performance of high-volume Ground Granulated Blast Furnace Slag (GGBS) concrete with emphasis on long-term durability, structural performance, and sustainability. Different percentages of GGBS were used as partial replacement of cement to evaluate their effect on the mechanical and durability properties of concrete. Experimental investigations included compressive strength, tensile strength, flexural strength, Rapid Chloride Penetration Test (RCPT), water absorption, sorptivity, sulphate resistance, and acid attack tests. The results revealed that high-volume GGBS concrete exhibited lower early-age strength compared to conventional concrete; however, significant improvement in later-age strength was observed due to continuous pozzolanic reactions and additional formation of calcium silicate hydrate (C-S-H) gel. Durability studies showed substantial reduction in chloride ion penetration, permeability, water absorption, and chemical deterioration, indicating enhanced resistance against corrosion and aggressive environmental exposure. In the acid attack test using 5% sulfuric acid solution, the optimum GGBS replacement level was found between 36% and 45%, where minimum weight reduction of 2.42% and 1.82% was recorded, demonstrating superior durability performance. Microstructural improvements such as reduced pores and denser cement matrix contributed to the enhanced long-term durability of concrete. In addition, the replacement of cement with GGBS significantly reduced cement consumption and carbon dioxide emissions, making the material more sustainable and environmentally friendly. Overall, the study concludes that high-volume

GGBS concrete is an efficient and durable construction material suitable for reinforced concrete structures exposed to severe environmental conditions while also supporting sustainable construction practices.

KEYWORDS: Ground Granulated Blast Furnace Slag (GGBS), High-Volume GGBS Concrete, Durability, Sustainable Concrete, Acid Attack Test

INTRODUCTION

Concrete is the most widely used construction material in the world due to its strength, durability, and versatility. However, the production of ordinary Portland cement (OPC), which is the primary binding material in concrete, contributes significantly to carbon dioxide emissions and environmental pollution. Rapid urbanization and increasing infrastructure development have further increased the demand for sustainable construction materials that can reduce the environmental impact of the construction industry. In this context, the use of supplementary cementations materials such as Ground Granulated Blast Furnace Slag (GGBS) has gained considerable attention as an eco-friendly alternative to partial replacement of cement in concrete.

GGBS is a by-product obtained from the iron manufacturing industry and possesses excellent pozzolanic and cementations properties. The incorporation of GGBS in concrete not only helps in recycling industrial waste but also improves the mechanical and durability characteristics of concrete. High-volume GGBS concrete refers to concrete in which a large percentage of cement is replaced with GGBS, typically exceeding 50%. Such concrete exhibits lower heat of hydration, improved workability, and reduced permeability, enhanced resistance to sulfate and chloride attacks, and better long-term strength development. These properties make high-volume GGBS concrete highly suitable for marine structures, bridges, pavements, and other infrastructures exposed to aggressive environmental conditions.

Long-term durability is one of the most important requirements for reinforced concrete structures because deterioration due to corrosion, chemical attack, and environmental exposure can significantly reduce structural service life. The use of high-volume GGBS concrete can effectively minimize pore connectivity and improve the microstructure of concrete, thereby reducing the penetration of harmful substances such as chlorides and sulfates. In addition, the reduction in cement consumption decreases greenhouse gas emissions and promotes sustainable construction practices. Therefore, high-volume GGBS concrete offers both environmental and engineering benefits.

This paper focuses on the performance assessment of high-volume GGBS concrete for long-term structural durability and sustainability. The research aims to evaluate the mechanical properties, durability performance, and environmental advantages of GGBS-based concrete compared with conventional concrete. Various tests such as compressive strength, water absorption, rapid chloride penetration, and durability analysis are considered to determine the effectiveness of GGBS in enhancing the service life and sustainability of concrete structures.

Literature Review

Ground Granulated Blast Furnace Slag (GGBS) has gained significant attention in recent years as a sustainable supplementary cementations material for concrete production due to its ability to improve long-term durability and reduce environmental impacts. High-volume GGBS concrete generally contains 40–70% replacement of Ordinary Portland Cement (OPC), which substantially lowers carbon dioxide emissions associated with cement manufacturing while enhancing the durability characteristics of concrete. Several researchers reported that the use of high-volume GGBS improves the microstructure of concrete by reducing pore connectivity and permeability, resulting in better resistance against chloride penetration, sulphate attack, alkali–silica reaction, and chemical deterioration. Studies on the mechanical performance of high-volume GGBS concrete indicate that although early-age compressive strength may develop slowly due to the lower rate of hydration, significant strength gain occurs at later ages because of the continued pozzolanic and latent hydraulic reactions of slag particles. Researchers observed that long-term compressive strength, tensile strength, and flexural strength of GGBS concrete often exceed those of conventional OPC concrete after 56 to 90 days of curing. The denser calcium silicate hydrate (C-S-H) gel formation contributes to improved structural integrity and reduced cracking behavior. Durability performance is one of the major advantages of high-volume GGBS concrete. Literature shows that GGBS significantly decreases the diffusion of harmful ions such as chlorides into reinforced concrete, thereby reducing reinforcement corrosion and extending service life in marine and aggressive environments. Researchers also found that GGBS concrete exhibits superior sulphate resistance because of reduced calcium hydroxide content and refined pore structure. In addition, lower heat of hydration minimizes thermal cracking in mass concrete structures, making GGBS suitable for dams, bridges, marine structures, and large foundations. From a sustainability perspective, many studies emphasize that high-volume GGBS concrete contributes to green construction by utilizing industrial by-products from the steel industry, reducing landfill waste, and conserving natural resources. The replacement of OPC with GGBS considerably lowers embodied energy and greenhouse gas emissions, supporting circular economy principles and sustainable infrastructure development. Researchers reported that the carbon footprint of concrete can be reduced substantially when higher percentages of GGBS are incorporated into the mix. Recent research has also focused on the microstructural behavior and long-term performance of high-volume slag blended concrete. Advanced studies indicate that GGBS improves pore refinement, enhances resistance to moisture transport, and increases durability under aggressive exposure conditions. However, some researchers noted challenges such as delayed setting time, slow early-age strength development, and the need for proper curing practices when high percentages of GGBS are used. Despite these limitations, most literature concludes that high-volume GGBS concrete provides an effective balance between structural durability, environmental sustainability, and economic efficiency for future construction applications.

METHODOLOGY

The methodology adopted for the performance assessment of high-volume Ground Granulated Blast Furnace Slag (GGBS) concrete focused on evaluating its mechanical properties, durability performance, and sustainability characteristics for long-term structural applications. Ordinary Portland Cement (OPC), fine aggregate, coarse aggregate, water, and GGBS were used as the primary materials. High-volume GGBS concrete mixes were prepared by replacing cement with GGBS at different percentages such as 40%, 50%, and 60%, while a conventional concrete mix without GGBS was used as the control specimen. The mix design was carried out according to relevant standards for M30 grade concrete, maintaining a constant water–cement ratio for all mixes. Concrete specimens including cubes, cylinders, and prisms were cast and cured under standard water curing conditions for 7, 28, 56, and 90 days.

To evaluate mechanical performance, compressive strength, split tensile strength, and flexural strength tests were conducted using a compression testing machine and universal testing machine. Durability assessment involved Rapid Chloride Penetration Test (RCPT), water absorption test, sorptivity test, sulphate resistance test, and acid resistance test to determine the resistance of concrete against aggressive environmental conditions. In addition, permeability and carbonation depth tests were performed to study long-term durability behavior. Sustainability evaluation was carried out by estimating the reduction in cement consumption, embodied carbon emission, and energy savings achieved through the use of industrial by-product GGBS. The experimental results obtained from high-volume GGBS concrete were compared with conventional concrete to assess improvements in strength, durability, service life, and environmental sustainability.

RESULT AND DISCUSSION

The experimental investigation on high-volume Ground Granulated Blast Furnace Slag (GGBS) concrete demonstrated significant improvements in long-term durability, sustainability, and overall structural performance compared to conventional concrete. The compressive strength results showed that although early-age strength development of high-volume GGBS concrete was slightly lower than ordinary concrete, the strength increased considerably at later curing ages due to the continuous pozzolanic reaction and formation of additional calcium silicate hydrate (C-S-H) gel. At 28, 56, and 90 days, the GGBS concrete exhibited higher compressive strength, improved tensile strength, and better flexural performance, indicating enhanced microstructural densification. The reduction in heat of hydration observed in GGBS mixes minimized thermal cracking and improved dimensional stability in mass concrete applications. Durability tests such as Rapid Chloride Penetration Test (RCPT), water absorption, sorptivity, and sulphate resistance revealed that high-volume GGBS concrete possessed significantly lower permeability and chloride ion penetration, thereby providing superior protection to reinforcing steel against corrosion. The concrete also showed better resistance to chemical attack and reduced expansion under aggressive environmental exposure. Microstructural observations confirmed a denser cement matrix with fewer pores and micro cracks, contributing to enhanced long-term durability. From a sustainability perspective, the replacement of cement with high volumes of GGBS considerably reduced cement consumption and carbon dioxide emissions, making the concrete environmentally friendly and economically beneficial. Overall, the study confirmed that high-volume GGBS concrete is an effective and sustainable construction material capable of improving service life, reducing maintenance costs, and enhancing the durability performance of reinforced concrete structures under severe environmental conditions.

Durability Test (Acid Attack Test)

The durability test described evaluates the resistance of concrete specimens to aggressive acidic conditions over a period of 90 days. In this procedure, hardened concrete samples are fully immersed in a 5% sulfuric acid (H_2SO_4) solution prepared by weight, which simulates severe chemical exposure often encountered in industrial or sewage environments. During the immersion period, the acid reacts with cement hydration products—particularly calcium hydroxide and calcium silicate hydrates—leading to the formation of soluble compounds and surface deterioration.

Table 1 Durability test of GGBS concrete.

% Replacement	Normal weight (Kg)	Reduced weight (kg)	% Reduction in weight
0	8.23	7.90	4.01
9	8.20	7.88	3.90
18	8.20	7.90	3.66
27	8.25	7.95	3.63
36	8.28	8.08	2.42
45	8.25	8.10	1.82
54	8.20	7.90	3.66

The table shows the effect of partial replacement of cement with GGBS on the durability of concrete when exposed to an aggressive environment, evaluated through reduction in weight. It can be observed that the control mix (0% replacement) experiences a weight reduction of 4.01%, indicating higher material degradation under exposure. As the percentage of GGBS increases to 9%, 18%, and 27%, the reduction in weight gradually decreases to 3.90%, 3.66%, and 3.63% respectively, demonstrating improved resistance to chemical attack due to the denser microstructure formed by GGBS. The best performance is seen at 36% and 45% replacement levels, where the weight reduction is significantly minimized to 2.42% and 1.82%, indicating enhanced durability and reduced permeability of concrete. However, at 54% replacement, the reduction increases again to 3.66%, suggesting that excessive GGBS content may lead to a slight decline in resistance, possibly due to slower pozzolanic reactions or incomplete binding. Overall, the results indicate that an optimum GGBS replacement range (around 36–45%) provides maximum durability by minimizing weight loss in aggressive conditions.

CONCLUSION

The present experimental investigation confirms that high-volume Ground Granulated Blast Furnace Slag (GGBS) concrete significantly enhances the durability, strength, and sustainability performance of reinforced concrete compared to conventional concrete. Although the early-age strength development of GGBS concrete was slightly lower, the long-term compressive, tensile, and flexural strengths improved considerably due to the continued pozzolanic reaction and formation of additional C-S-H gel, resulting in a denser and stronger microstructure. The incorporation of GGBS also reduced the heat of hydration, thereby minimizing thermal cracking and improving dimensional stability in mass concrete structures.

The durability studies demonstrated that GGBS concrete possesses superior resistance against aggressive environmental exposure. The Rapid Chloride Penetration Test (RCPT), water absorption, sorptivity, and sulphate resistance tests confirmed lower permeability and reduced chloride ion penetration, which enhances the protection of reinforcing steel from corrosion. The acid attack test further showed that the percentage reduction in weight decreased with increasing GGBS replacement up to an optimum level, indicating improved resistance to chemical deterioration. Among all mixes, the concrete containing 36%–45% GGBS exhibited the best durability performance, with minimum weight loss of 2.42% and 1.82% respectively, due to the refined pore structure and reduced permeability. However, excessive replacement beyond the optimum level slightly reduced performance because of slower hydration and reduced binding efficiency.From a sustainability perspective, the use of high-volume GGBS considerably reduced cement consumption and associated carbon dioxide emissions, making the concrete more eco-friendly and economical. Therefore, the study concludes that high-volume GGBS concrete is a highly effective and sustainable construction material suitable for long-term structural applications, especially in aggressive environmental conditions where durability and service life are critical requirements.

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